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A MATHEMATICAL MODEL OF ELECTROSTATIC PRECIPITATION (REVISION 3): VOLUME I MODELING AND PROGRAMMING

by

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16. ABSTRACT

The report documents briefly the fundamental mechanisms and limiting factors involved in electrostatic precipitation. It also discusses theories and procedures used in a model to describe the physical mechanisms. It generally describes the major operations performed in a computer program, lists the entire computer program, and defines all variables used in the program. Improvements in the model include a new way to calculate solutions to the electric field equations, a dynamic way to describe the effects of rapping reentrainment, a way to calculate effluent opacity, and a way to check the input data. Revision 3 of the model calculates efficiency in about 10% of the time required by Revision 1. The option to use input data expressed entirely in the metric system is provided, as are options to terminate the calculation after calculating V-I curves and to use an internal data set to estimate precipitator efficiency based on the resistivity of the dust particles. Computer program subroutines that perform fundamental calculations or utilize numerical techniques are described in sufficient detail to provide an understanding of their content and usage. A detailed flow chart is provided for each subroutine. Input and output variables are described, and limitations on these variables are noted.

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a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Electrical Resistivity	Pollution Control	13B	
Electrostatic Precipitation		Stationary Sources	13H	
Mathematical Models			12A	
Electric Fields			20C	
Opacity	Dust		14G	11G
Efficiency				

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ABSTRACT

The objectives of this research program were to upgrade the existing model of electrostatic precipitation developed under the sponsorship of the Environmental Protection Agency, to make the computer program which performs the calculations required by the model more user oriented, and to fully document those subroutines in the computer program that perform fundamental calculations or utilize numerical techniques.

In this report, the fundamental mechanisms and limiting factors involved in the electrostatic precipitation process are described briefly. The theories and procedures used in the model to describe the physical mechanisms are discussed. A general description of the major operations which are performed in the computer program is given. A listing of the entire computer program and the definitions of all the variables used in the program are provided.

Improvements to the model include a new method of calculating the solutions to the electric field equations, a dynamic method of describing the effects of rapping reentrainment, a procedure for calculating effluent opacity, and a routine which checks the input data. Revision 3 of the model performs efficiency calculations in approximately 10% of the time required by Revision 1. The option to use input data expressed entirely in the metric system is provided, as are options to terminate the calculation after the calculation of V-I curves and to use an internal data set to estimate precipitator efficiency based on the resistivity of the dust particles.

Those subroutines in the computer program that perform fundamental calculations or utilize numerical techniques are described in sufficient detail to provide an understanding of their content and usage. A detailed flow chart is provided for each of these subroutines. Input and output variables are described and any limitations on these variables are noted.

A complete description of the input data to the computer program is provided so that the program can be utilized. Modifications which can be made to the computer program to adapt it to different computers and to extend its capabilities are discussed.

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NOMENCLATURE

w_p	Migration velocity near the collection electrode of a particle of radius a, m/sec
q	Charge on a particle, coul
E_p	Electric field near the collection electrode, V/m
a	Particle radius, m
μ	Gas viscosity, kg/m-sec
C	Cunningham correction factor (or slip correction factor)
λ	Mean free path of gas molecules, m
A'	Quantity defined by $[1.257 + 0.4 \exp(-1.1\, a/\lambda)]$
η_m	Collection fraction for a monodisperse aerosol
A_p	Collection electrode area, m^2
Q	Gas volume flow rate, m^3/sec
V_L	Voltage drop across the collected particulate layer, V
j	Current density in the collected particulate layer, A/cm^2
ρ'	Resistivity of the collected particulate layer, ohm-cm
t	Thickness of the collected particulate layer, cm
E_L	Average electric field in the collected particulate layer, V/cm
$\eta_{i,j}$	Ideal collection fraction for the i-th particle size in the j-th increment of length of the precipitator
$w_{i,j}$	Migration velocity of the i-th particle size in the j-th increment of length of the precipitator, m/sec
A_j	Collection electrode area in the j-th increment of length of the precipitator, m^2

η_i	Ideal collection fraction for a given particle size over the entire length of the precipitator
$N_{i,j}$	Number of particles of the i-th particle size per cubic meter of gas entering the j-th increment, $\#/m^3$
η	Ideal overall mass collection efficiency for the entire polydisperse aerosol, %
P_i	Percentage by mass of the i-th particle size in the inlet size distribution, %
V	Electric potential at a given point in a precipitator, V
ρ	Total space charge density at a given point in the gas in a precipitator, $coul/m^3$
b_e	Effective charge carrier mobility, $m^2/V\text{-}sec$
y	Coordinate parallel to the gas flow from wire-to-wire, m
x	Coordinate perpendicular to the gas flow from wire-to-plate, m
ε_0	Permittivity of free space, $coul/N\text{-}m^2$
J_p	Average current density at the collection plate, A/m^2
ρ_{pi}	Space charge densities for various points on the collection plate, $coul/m^3$
E_{pi}	Electric field strengths for various points on the collection plate, V/m
N	Number of grid points in the direction of gas flow in the electric field calculations
q	Instantaneous particle charge, coul
q_s	Saturation charge due to field charging, coul
θ	Azimuthal angle in a spherical coordinate system with origin at the center of the particle, radians
θ_0	Maximum azimuthal angle for which electric field lines enter a charged particle, radians
N_0	Free ion density, $\#/m^3$
e	Electronic charge, coul

E_0	Average electric field between the discharge electrodes, V/m
b	Ion mobility, m^2/V-sec
$\tilde{v}$	Mean thermal speed of ions, m/sec
k	Boltzmann's constant, J/°K
T	Absolute temperature of the gas, °K
t	Time, sec
K	Dielectric constant of the particle
r_0	Radial distance along θ at which the radial component of the total electric field is zero, m
q_D	Charge predicted from classical diffusion charging theory, coul
q_F	Charge predicted from classical field charging theory, coul
t_i	Initial time for charging under a fixed set of conditions, sec
t_f	Final time for charging under a fixed set of conditions, sec
q_j	Charge on the particle at time t_i, coul
b'	Effective ion mobility, m^2/V-sec
j_t	Total current density at the collection plate due to ions and particles, A/m^2
j_p	Particulate current density at the collection plate, A/m^2
w	Migration velocity for a given particle diameter which is calculated from fundamental principles and applies only to a given length increment as used in the model, cm/sec
w_e	Effective migration velocity for a given particle diameter which is calculated from fundamental principles and applies to the entire length of the precipitator, cm/sec
w_e'	Apparent effective migration velocity for a given particle diameter which is obtained by making an empirical correction (or corrections) to w_e, cm/sec

w_{pr}	precipitation rate parameter which provides a measure of how well the entire mass which enters the precipitator will be collected, cm/sec
F_i	Particle diameter-dependent correction factors for nonuniform gas velocity distribution
σ_g	Normalized standard deviation of the gas velocity distribution
P_{N_S}	Penetration of a given particle size from the last baffled section which is corrected for gas sneakage
S	Fractional amount of gas sneakage per baffled section
N_s	Number of baffled sections
B_i	Particle diameter-dependent correction factors for gas sneakage and/or nonrapping reentrainment
$w_{e,i}$	Effective migration velocity for the i-th particle diameter, cm/sec
$w'_{e,i}$	Apparent effective migration velocity for the i-th particle diameter, cm/sec
P_{N_R}	Penetration of a given particle size which is corrected for nonrapping reentrainment
R	Fraction of collected material reentrained per section
N_R	Number of sections over which reentrainment is assumed to occur
η'/section	Total mass collection fraction per linear electrical section under normal operating conditions
η_0	Overall mass collection fraction determined from mass train measurements under normal operating conditions
X'	Quantity which is equal to $-\ln(1-\eta_0)$
N_E	Number of electrical sections in series
X	Calculated mass removal by the last electrical section, mg/DSCM
y_1	Measured rapping emissions from cold-side precipitators, mg/DSCM
y_2	Measured rapping emissions from hot-side precipitators, mg/DSCM

d_{50} (MMD)	Mass median diameter of a log-normal particle size distribution, μm
σ_p	Geometric standard deviation of a log-normal particle size distribution
V_w	Applied voltage, V
S_x	Wire-to-plate spacing, m
S_y	One half wire-to-wire spacing, m
r_w	Radius of corona wire, m
a_x	Increment size in the x-direction used in calculating electrical conditions, m
a_y	Increment size in the y-direction used in calculating electrical conditions, m
E_x	x-component of the electric field, V/m
E_y	y-component of the electric field, V/m
V_0	Electric potential at an arbitrary point in a numerical grid, V
ρ_0	Space charge density at an arbitrary point in a numerical grid, $coul/m^3$
α	Parameter in the equation for ρ_0, $coul/m^3$
β	Parameter in the equation for ρ_0, $coul^2/m^6$
α_{AB}	Values of α along a line from wire to wire, $coul/m^3$
α_{BC}	Values of α along a line midway between wires from the plane of the wires to the plate, $coul/m^3$
α_{AD}	Values of α along a line from the wire to the plate, $coul/m^3$
α_{CD}	Values of α along the plate, $coul/m^3$
β_{AB}	Values of β along a line from wire to wire, $coul^2/m^6$
β_{BC}	Values of β along a line midway between wires from the plane of the wires to the plate, $coul^2/m^6$
β_{AD}	Values of β along a line from the wire to the plate, $coul^2/m^6$

β_{CD}	Values of β along the plate, $coul^2/m^6$
ρ_s	Space charge density at the outer boundary of the ionized corona sheath, $coul/m^3$
b_s	Effective charge carrier mobility at the outer boundary of the ionized corona sheath, $m^2/V\text{-}sec$
f	Roughness factor of the corona wires
δ	Relative density of the gas
ρ_w	Space charge density near the corona wire, $coul/m^3$
r_s	Radius of the ionized corona sheath, m
E_s	Electric field at the outer boundary of the ionized corona sheath, V/m
E_c	Corona starting electric field, V/m
$\frac{dy}{dx}$	Derivative of the variable y with respect to the variable x where x and y represent unspecified quantities
$f(x,y)$	Arbitrary function of x and y
k_n	Weighting factors in a Runge-Kutta integration scheme ($n = 1,2,3,4$)
Δy	Increment for advancing the dependent variable in the Runge-Kutta integration scheme
h	Increment size for the independent variable in the Runge-Kutta, Simpson's Rule, and trapezoidal rule integration schemes
$x_n(x_i)$	Values of the independent variable in the Runge-Kutta and Simpson's Rule integration schemes
$y_n(y_i)$	Values of the dependent variable in the Runge-Kutta, Simpson's Rule, and trapezoidal rule integration schemes
n	Number of charges on a particle
c_1	Coefficient of X in the cubic equation (53)
c_2	Factor in the constant term in the cubic equation (53)
$f_{L-N}(z)$	Log-normal distribution function

d	Particle diameter, μm
z	Independent variable for the log-normal distribution
$\bar{z}$	Mean value of z
σ_z	Standard deviation of z
M	Total mass contained in a log-normal particle size distribution, kg/m^3
F_i	Mass fractions for the different size bands in a log-normal particle size distribution
S_i	Cumulative mass fractions in a log-normal particle size distribution
Z_i	Cumulative integrals obtained in a trapezoidal rule integration
$S(X)$	Cumulative fraction up to a given particle size in a log-normal distribution
t	Transformation variable for a log-normal distribution
t'	Lower limit for the integration of a Gaussian integral over the variable t
$Q(t)$	Cumulative fraction greater than a given particle size
ϕ	Variable in terms of which t can be expressed
a_0, a_1, a_2	Coefficients in an approximate expression for t'
b_1, b_2, b_3	Coefficients in an approximate expression for t'
z'	Natural logarithm of a known or measured particle diameter corresponding to a known or measured cumulative mass fraction
$\bar{z}'$	Mean value of z'
A	Quantity which is equal to $-\bar{z}'/\sigma_z$
B	Quantity which is equal to $1/\sigma_z$
m	Number of data points in a least squares fit to a straight line
Δ	Parameter obtained in a least squares fit to a straight line

r	Linear-correlation coefficient
$\bar{J}_\ell$	Average current density in the l-th subincremental length of a given length increment, A/m^2
$\bar{E}_\ell$	Average electric field in the l-th subincremental length of a given length increment, V/m
$\bar{\rho}_\ell$	Average total particulate charge density in the l-th subincremental length of a given length increment, $coul/m^3$
$\bar{\rho}_{i,\ell}$	Average charge density for the i-th particle size at the end of the l-th subincremental length of a given length increment, $coul/m^3$
$x_{i,\ell}$	Number of particles per unit volume of gas of the i-th particle size entering the l-th subincremental length of a given length increment, $\#/m^3$
$q_{i,\ell}$	Charge on the i-th particle size at the end of the l-th subincremental length of a given length increment, coul
$\bar{b}_\ell$	Weighted particulate mobility due to all particles in the l-th subincremental length of a given length increment, $m^2/V\text{-}sec$
C_i	Cunningham correction factor (or slip correction factor) for the i-th particle size
a_i	Radius of the i-th particle size, m
X_ℓ	Total number of particles per unit volume of gas entering the l-th subincremental length of a given length increment, $\#/m^3$
$\bar{\rho}'_\ell$	Average ionic charge density with a particulate mass loading in the l-th subincremental length of a given length increment, $coul/m^3$
b'	Molecular ion "effective mobility", $m^2/V\text{-}sec$
$\bar{\rho}''_\ell$	Average ionic charge density without a particulate mass loading in the l-th subincremental length of a given length increment, $coul/m^3$
$\Delta\bar{\rho}_\ell$	Average charge density shifted from molecular ions to particles in the l-th subincremental length of a given length increment, $coul/m^3$

b_ℓ^e	Effective mobility due to both ions and particles in the l-th subincremental length of a given length increment, m^2/V-sec
$w_{i,\ell}$	Migration velocity of the i-th particle size in the l-th subincremental length of a given length increment, m/sec
$\bar{E}_\ell^p$	Average electric field at the collection plate in the l-th subincremental length of a given length increment, V/m
$\eta_{i,\ell}$	Ideal collection fraction for the i-th particle size in the l-th subincremental length of a given length increment
b^e	Average effective mobility for ions and particles over a length equal to one wire-to-wire spacing, m^2/V-sec
$\bar{J}_w$	Average current density near the wire without particles, A/m^2
$\bar{J}_w'$	Average current density near the wire with particles, A/m^2
A_p'	Collection plate area receiving current from a single wire, m^2
A_w	Surface area of a single wire, m^2
$\bar{J}_p$	Average current density at the collection plate for an area receiving current without particles from a single wire, A/m^2
$\bar{J}_p'$	Average current density at the collection plate for an area receiving current with particles from a single wire, A/m^2

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METRIC CONVERSION FACTORS

Length:	ft = 3.28 * m
	in. = 0.394 * cm
Area:	ft^2 = 10.8 * m^2
SCA:	ft^2/(1000 CFM) = 5.05 * m^2/(m^3/sec)
Linear flow:	ft/sec = 3.28 * m/sec
Volume flow:	ft^3/min = 2120 * m^3/sec
Mass:	grain = 15.6 * g
Mass loading:	grn/SCF = 0.442 * g/m^3
Temperature:	°F = (9/5 * °C) + 32
Current density:	μA/ft^2 = 0.926 * nA/cm^2

SECTION 1

INTRODUCTION

The electrostatic precipitation process involves several complicated and interrelated physical mechanisms: the creation of a nonuniform electric field and ionic current in a corona discharge; the ionic and electronic charging of particles moving in combined electro- and hydro-dynamic fields; and the turbulent transport of charged particles to a collection surface. The removal of the collected particulate layer from the collection surface presents a serious problem in many practical applications since the removal procedures introduce collected material back into the gas stream and cause a reduction in collection efficiency. Other practical considerations which reduce the collection efficiency are nonuniform gas velocity distribution, bypassage of the electrified regions by particle-laden gas, and particle reentrainment during periods when no attempt is being made to remove the collected material.

In recent years, increasing emphasis has been placed on developing theoretical relationships which accurately describe the individual physical mechanisms involved in the precipitation process and on incorporating these relationships into a complete mathematical model for electrostatic precipitation. From a practical standpoint, a reliable theoretical model for electrostatic precipitation would offer several valuable applications:

(1) precipitator design could be easily and completely performed by calculation from fundamental principles;

(2) a theoretical model could be used in conjunction with a pilot-plant study in order to design a full-scale precipitator;

(3) precipitator bids submitted by various manufacturers could be evaluated by a purchaser with respect to meeting the design efficiency and the costs necessary to obtain the design efficiency;

(4) the optimum operating efficiency of an existing precipitator could be established and the capability to meet particulate emissions standards could be ascertained; and

(5) an existing precipitator performing below its optimum efficiency could be analyzed with respect to the different operating variables in a procedure to troubleshoot and diagnose problem areas.

In addition to its many applications, a mathematical model can be a valuable tool for analyzing precipitator performance due to its cost and time savings capability. The approach is cost effective because it (1) allows for the analysis and projection of precipitator operation based upon a limited amount of data (extensive field testing is not necessary), (2) can predict trends caused by changing certain precipitator parameters and thus, in many cases, can prevent costly modifications to a precipitator which will not significantly improve the performance, (3) can be used as a tool in sizing precipitators and prevent excessive costs due to undersizing or significant oversizing, and (4) can be used to obtain large amounts of information without extensive use of manpower but, instead, with reasonable use of a computer.

The approach is time effective because (1) large amounts of information can be generated quickly, (2) it does not necessarily depend on time-consuming field tests which involve travel, extensive analysis, and plant and precipitator shut-downs, (3) it can prevent losses in time due to unnecessary or insufficient modifications to a precipitator, and (4) it can prevent losses in time due to the construction of an undersized precipitator.

In the present work, a revised model of electrostatic precipitation developed by Southern Research Institute under the sponsorship of the Environmental Protection Agency (Industrial Environmental Research Laboratory, Research Triangle Park) is discussed. Previous versions of the model are described in the publications entitled "A Mathematical Model of Electrostatic Precipitation".[1,2,3,4] The present report is separated into two volumes. Volume 1 contains a description of the physical mechanisms involved in the electrostatic precipitation process, the physical and mathematical formulation of the model, and a documentation of a computer program which implements the model. Volume 2 is a user's manual which describes how to use the model for various purposes. This volume includes a description of input and output data and relates these quantities to the various applications of the model.

Revision 1 of the model has the following features:

(1) it predicts collection efficiency as a function of particle diameter, electrical operating conditions, and gas properties;

(2) it can calculate clean-plate, clean-air voltage-current characteristics for wire-plate geometries;

(3) it determines particle charging by unipolar ions as a function of particle diameter, electrical conditions, and residence time;

(4) it can estimate the effects of particles on the electrical conditions under the assumption that effects due to the particulate layer can be ignored;

(5) it accounts for electrical sectionalization;

(6) it predicts particle capture at the collection electrode based on the assumptions of completely-random, turbulent flow, uniform gas velocity, and particle migration velocities which are small compared to the gas velocity;

(7) it employs empirical correction factors which adjust the particle migration velocities obtained without rapping losses;

(8) it accounts for the nonideal effects of nonuniform gas velocity distribution, gas bypassage of electrified regions, and particle reentrainment from causes other than rapping by using empirical correction factors to scale down the ideally-calculated particle migration velocities; and

(9) it accounts for rapping reentrainment by using empirical relationships for the quantity and size distribution of the reentrained mass.

Revision 2 of the model retained these features and offered reduced computer run time through a different integration procedure in the particle charging routine. Revision 2 also featured an analytic approximation to the solutions of the electric field equations which further reduced the required computer time. The version of the model presented in this work (Revision 3) offers the following features in addition to those of the previous revisions:

(1) the time required to solve the electric field equations is significantly reduced through the method of dominant eigenvalues;[5]

(2) the plume opacity of the ESP effluent may be calculated;

(3) input data may be expressed entirely in the metric system as well as in the mixed English-metric units used in previous revisions;

(4) rapping reentrainment corrections may be performed by reintroducing a portion of the collected dust layer into the gas stream rather than by the empirical correction of the previous revisions, if desired;

(5) an internal data set is provided for rough estimates of ESP sizing needs based on particle resistivity; and

(6) a routine to check for abnormal or missing input data has been added.

The changes and additions in this version of the model are summarized in Table 1. Due to the enhanced speed of the electric field calculations, the analytic field approximation developed for Revision 2 has been deleted from this version.

Certain features of this revision require more input data than the basic data sets used in Revisions 1 and 2. However, the model is structured so that input data sets for Revisions 1 and 2 may be used without changes to yield the same data as before in less time.

TABLE 1. ESP MODEL REVISION SUMMARY

Process	Revision
Estimation procedure	1,2,3
Electric field calculation	
rigorous calculation	1,2
same with dominant eigenvalues (faster)	3
analytic approximation	2
Particle charging calculation	
Simpson's rule integration	1
Gaussian integration (faster)	2,3
Correction for non-ideal effects	
sneakage, velocity distribution, non-rapping reentrainment	1,2,3
empirical rapping calculation	1,2,3
dynamic rapping calculation	3
Opacity calculation	3
Option of metric input data	3
Option to reduce printed output	3
Internal data set	3
VI curve generation	1,2,3
Option to stop after printing VI curve	3
Routine to check input data	3

SECTION 2

CONCLUSIONS

The main improvement in Revision 3 of the ESP model is the reduced computer time required for the rigorous calculations of particle charges and electric fields. The time required to run the program has been reduced to about one tenth of the time needed for Revision 1. The possibility of further time reduction by using particle charges predicted by a curve fit to a few calculated values rather than rigorously calculating charges for all particle sizes was investigated. Both polynomial and spline fits proved to be insufficiently accurate to warrant replacement of the existing charge calculation procedure.

Several new routines have been added to expand the usefulness of the model. The new version of the model will run with the same data sets as the previous versions, although shorter run times will result from changing one of the input parameters (NN). Program users may convert Revisions 1 and 2 of the ESP model to the latest version by making changes in the main routine and seven subroutines (CMAN, EFLD1, EFLD2, CHARGN, RATE, ADJUST, and PRTINP), deleting the data block and subroutine EFLD3 (Revision 2), and adding the seven new subroutines.

SECTION 3

RECOMMENDATIONS

Although the mathematical model of electrostatic precipitation presented in this report represents a significant improvement over the previous version, additional work needs to be performed in order to improve the fundamental basis and user oriented aspects of the model. Therefore, it is recommended that the following research be pursued:

1. Theoretical and experimental studies of the effects of particles on the electrical conditions should be continued in order to better describe the effect on the electric field distribution.

2. Theoretical and experimental studies of electrical breakdown mechanisms in the collected particulate layer should be given greater emphasis in an attempt to acquire the capability of theoretical prediction of when electrical breakdown will ensue for a given value of dust resistivity.

3. Since the model underpredicts field-measured collection efficiencies for fine particles without the use of empirical correction factors, theoretical and experimental studies should be continued in order to remove the empiricism or to explain the discrepancy. These studies should include a reevaluation of the theories presently used in the model and an examination of those effects which are presently neglected such as particle charging near corona wires and phenomena due to the gas flow field. There is evidence[6] that free electrons may play a role in particle charging in negative coronas for temperatures of 150°C to 350°C. A charging theory which accounts for this effect is needed.

4. Theoretical and experimental studies should be performed on the mechanisms involved in separating the dust layer from the collection plates during a rap and on the quantity and nature of the dust reentrained into the gas flow. This would provide an analytical method of determining the nature of the reentrained dust used in the dynamic rapping procedure and reduce the dependence on empirically derived data. This change would increase the usefulness of the model in optimizing the electrical operating conditions and the rapping schedule and intensity of an ESP.

5. Alternative numerical techniques need to be investigated and implemented in order to make the computer program run significantly faster.

SECTION 4

FUNDAMENTAL STEPS IN THE ELECTROSTATIC PRECIPITATION PROCESS

CREATION OF AN ELECTRIC FIELD AND CORONA CURRENT

The first step in the precipitation process is the creation of an electric field and corona current. This is accomplished by applying a large potential difference between a small-radius electrode and a much larger radius electrode, where the two electrodes are separated by a region of space containing an insulating gas. For industrial applications, a large negative potential is applied at the small-radius electrode and the large-radius electrode is grounded.

At any applied voltage, an electric field exists in the interelectrode space. For applied voltages less than a value referred to as the "corona starting voltage", a purely electrostatic field is present. At applied voltages above the corona starting voltage, the electric field in the vicinity of the small-radius electrode is large enough to produce ionization by electron impact. Between collisions with neutral molecules, free electrons are accelerated to high velocities and, upon collision with a neutral molecule, their energies are sufficiently high to cause an electron to be separated from a neutral molecule. Then, as the increased number of electrons moves out from the vicinity of the small-radius electrode, further collisions between electrons and neutral molecules occur. In a limited high electric field region near the small-radius electrode, each collision between an electron and a neutral molecule has a certain probability of forming a positive molecular ion and another electron, and an electron avalanche is established. The positive ions migrate to the small-radius electrode and the electrons migrate into the lower electric field regions toward the large-radius electrode. These electrons quickly lose much of their energy and, when one of them collides with a neutral electro-negative molecule, there is a probability that attachment will occur and a negative ion will be formed. Thus, negative ions, along with any electrons which do not attach to a neutral molecule, migrate under the influence of the electric field to the large-radius electrode and provide the current necessary for the precipitation process.

Figure 1a is a schematic diagram showing the region very near the small-radius electrode where the current-carrying negative

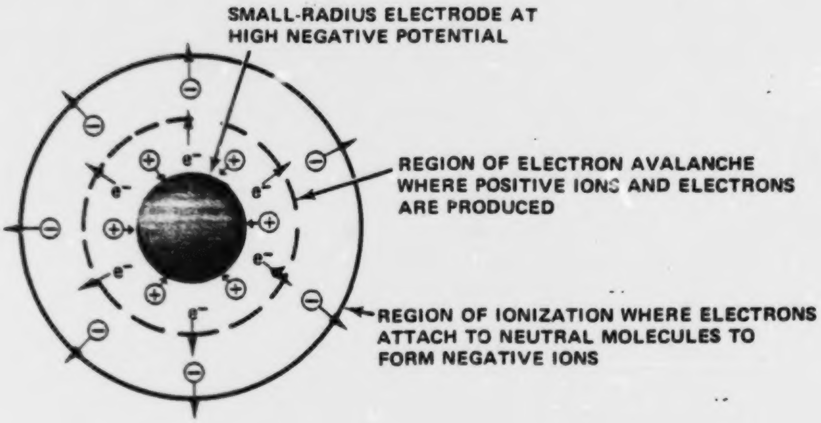

SMALL-RADIUS ELECTRODE AT HIGH NEGATIVE POTENTIAL
REGION OF ELECTRON AVALANCHE WHERE POSITIVE IONS AND ELECTRONS ARE PRODUCED
REGION OF IONIZATION WHERE ELECTRONS ATTACH TO NEUTRAL MOLECULES TO FORM NEGATIVE IONS
e⁻
⊕
⊖

Figure 1a. Region near small-radius electrode.

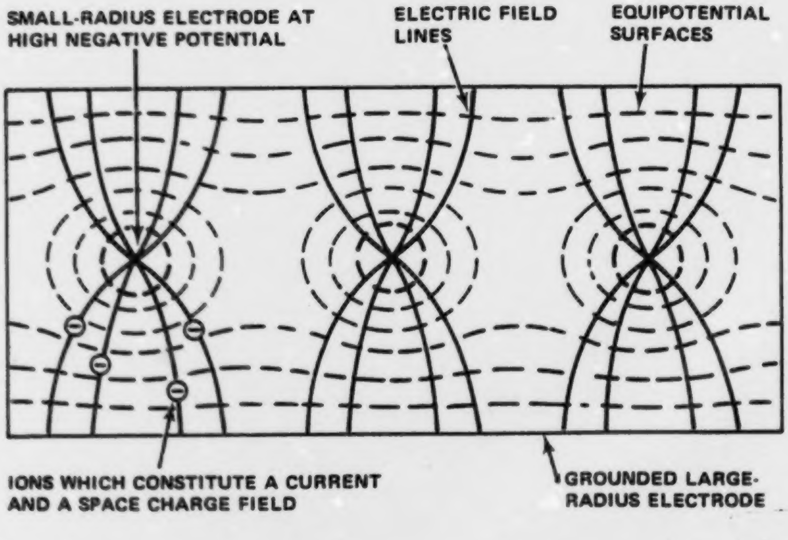

SMALL-RADIUS ELECTRODE AT HIGH NEGATIVE POTENTIAL
ELECTRIC FIELD LINES
EQUIPOTENTIAL SURFACES
⊖
IONS WHICH CONSTITUTE A CURRENT AND A SPACE CHARGE FIELD
GROUNDED LARGE-RADIUS ELECTRODE

Figure 1b. Electric field configuration for wire-plate geometry.

ions are formed. As these negative ions migrate to the large-radius electrode, they constitute a steady-state charge distribution in the interelectrode space which is referred to as an "ionic space charge". This "ionic space charge" establishes an electric field which adds to the electrostatic field to give the total electric field. As the applied voltage is increased, more ionizing sequences result and the "ionic space charge" increases. This leads to a higher average electric field and current density in the interelectrode space.

Figure 1b gives a qualitative representation of the electric field distribution and equipotential surfaces in a wire-plate geometry which is most commonly used. Although the electric field is very nonuniform near the wire, it becomes essentially uniform near the collection plates. The current density is very nonuniform throughout the interelectrode space and is maximum along a line from the wire to the plate.

In order to maximize the collection efficiency obtainable from the electrostatic precipitation process, the highest possible values of applied voltage and current density should be employed. In practice, the highest useful values of applied voltage and current density are limited by either electrical breakdown of the gas throughout the interelectrode space or of the gas in the collected particulate layer. High values of applied voltage and current density are desirable because of their beneficial effect on particle charging and particle transport to the collection electrode. In general, the voltage-current characteristics of a precipitator depend on the geometry of the electrodes, the gas composition, temperature, and pressure, the particulate mass loading and size distribution, and the resistivity of the collected particulate layer. Thus, maximum values of voltage and current can vary widely from one precipitator to another and from one application to another.

PARTICLE CHARGING

Once an electric field and current density are established, particle charging can take place. Particle charging is essential to the precipitation process because the electrical force which causes a particle to migrate toward the collection electrode is directly proportional to the charge on the particle. The most significant factors influencing particle charging are particle diameter, applied electric field, current density, and exposure time.

The particle charging process can be attributed mainly to two physical mechanisms, field charging and thermal charging.[7,8,9] These two mechanisms are discussed below.

(1) At any instant in time and location in space near a particle, the total electric field is the sum of the electric field

due to the charge on the particle and the applied electric field. In the field charging mechanism, molecular ions are visualized as drifting along electric field lines. Those ions moving toward the particle along electric field lines which intersect the particle surface impinge upon the particle surface and place charge on the particle.

Figure 2 depicts the field charging mechanism during the time it is effective in charging a particle. In this mechanism, only a limited portion of the particle surface $(0 \leq \theta < \frac{\pi}{2})$ can suffer an impact with an ion and collisions of ions with other portions of the particle surface are neglected. Field charging takes place very rapidly and terminates when sufficient charge (the saturation charge) is accumulated to repel additional ions. Figure 3b depicts the electric field configuration once the particle has attained the saturation charge. In this case, the electric field lines circumvent the particle and the ions move along them around the particle.

Theories based on the mechanism of field charging agree reasonably well with experiments whenever particle diameters exceed about 0.5 μm and the applied electric field is moderate to high. In these theories, the amount of charge accumulated by a particle depends on the particle diameter, applied electric field, ion density, exposure time, ion mobility, and dielectric constant of the particle.

(2) The thermal charging mechanism depends on collisions between particles and ions which have random motion due to their thermal kinetic energy. In this mechanism, the particle charging rate is determined by the probability of collisions between a particle and ions. If a supply of ions is available, particle charging occurs even in the absence of an applied electric field. Although the charging rate becomes negligible after a long period of time, it never has a zero value as is the case with the field charging mechanism. Charging by this mechanism takes place over the entire surface of the particle and requires a relatively long time to produce a limiting value of charge.

Figure 3a depicts the thermal charging process in the absence of an applied electric field. In this case, the ion distribution is uniform around the surface of the particle and each element of surface area has an equal probability of experiencing an ion collision. Thermal charging theories which neglect the effect of the applied electric field adequately describe the charging rate over a fairly broad range of particle sizes where the applied electric field is low or equal to zero. In addition, they work well for particles less than 0.2 μm in diameter regardless of the magnitude of the applied electric field.

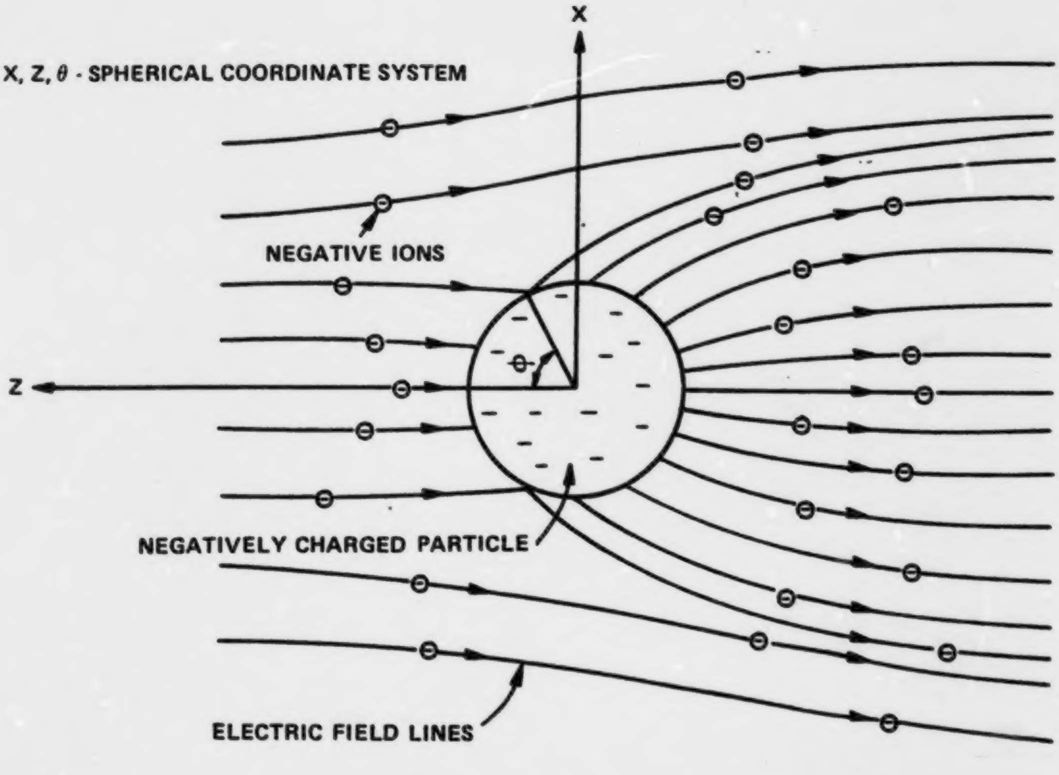

X
X, Z, θ - SPHERICAL COORDINATE SYSTEM
NEGATIVE IONS
Z
θ
NEGATIVELY CHARGED PARTICLE
ELECTRIC FIELD LINES

Figure 2. Electric field configuration during field charging.

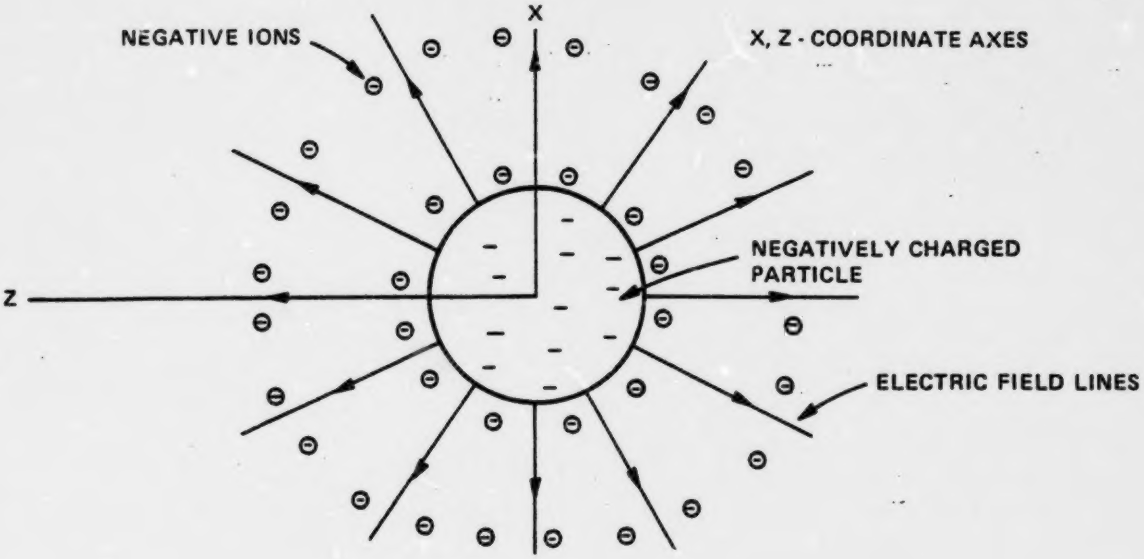

X
NEGATIVE IONS
X, Z - COORDINATE AXES
NEGATIVELY CHARGED PARTICLE
Z
ELECTRIC FIELD LINES

Figure 3a. Electric field configuration and ion distribution for particle charging with no applied field.

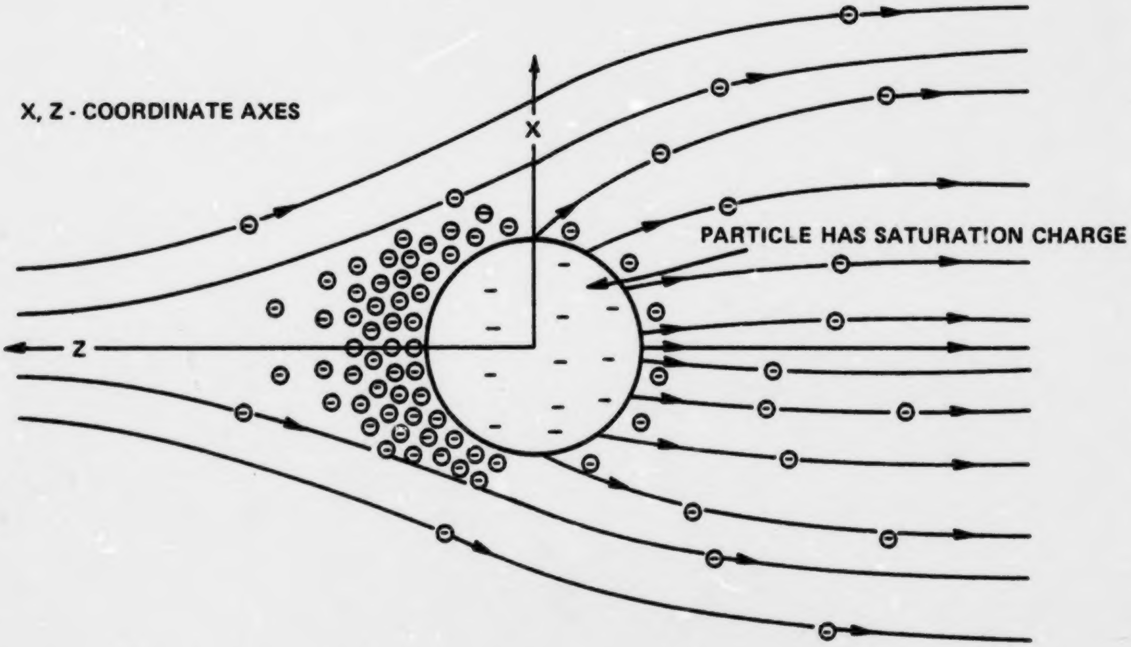

X, Z - COORDINATE AXES
X
PARTICLE HAS SATURATION CHARGE
Z

Figure 3b. Electric field configuration and ion distribution for particle charging in an applied field after saturation charge is reached.

Figure 3b depicts the thermal charging process in the presence of an applied electric field after the particle has attained the saturation charge determined from field charging theory. The effect of the applied electric field is to cause a large increase in ion concentration on one side of the particle while causing only a relatively small decrease on the other side. Although the ion concentration near the surface of the particle becomes very nonuniform, the net effect is to increase the average ion concentration, the probability of collisions between ions and the particle, and the particle charging rate.

In thermal charging theories, the amount of charge accumulated by a particle depends on the particle diameter, ion density, mean thermal velocity of the ions, absolute temperature of the gas, particle dielectric constant, residence time, and the applied electric field. The effect of the applied electric field on the thermal charging process must be taken into account for fine particles having diameters between 0.1 and 2.0 μm. Depending most importantly on the applied electric field and to a lesser extent on certain other variables, particles in this size range can acquire values of charge which are 2-3 times larger than that predicted from either the field or the thermal charging theories. For these particles, neither field nor thermal charging predominates and both mechanisms must be taken into account simultaneously.

In most cases, particle charging has a noticeable effect on the electrical conditions in a precipitator. The introduction of a significant number of fine particles or a heavy concentration of large particles into an electrostatic precipitator significantly influences the voltage-current characteristic. Qualitatively, the effect is seen by an increased voltage for a given current compared to the particle-free situation. As the particles acquire charge, they must carry part of the current but they are much less mobile than the ions. This results in a lower "effective mobility" for the charge carriers and, in order to obtain a given particle-free current, higher voltages must be applied to increase the drift velocities of the charge carriers and the ion densities.

The charged particles, which move very slowly, establish a "particulate space charge" in the interelectrode space. The distribution of the "particulate space charge" results in an electric field distribution which adds to those due to the electrostatic field and the ionic field to give the total electric field distribution. It is desirable to determine the space charge resulting from particles because of its influence on the electric field distribution, especially near the collection plate where, for the same current, the electric field is raised above the particle-free situation. In addition, the "particulate space charge" is a function of position along the length of the precipitator since particle charging and collection are a function of length.

PARTICLE COLLECTION

As the particle-laden gas moves through a precipitator, each charged particle has a component of velocity directed towards the collection electrode. This component of velocity is called the electrical drift velocity, or migration velocity, and results from the electrical and viscous drag forces acting upon a suspended charged particle. For particle sizes of practical interest, the time required for a particle to achieve a steady state value of migration velocity is negligible and, near the collection electrode, the magnitude of this quantity is given by[10]

$$w_p = \frac{qE_pC}{6\pi a\mu} , \qquad (1)$$

where w_p = migration velocity near the collection electrode of a particle of radius a (m/sec),

q = charge on particle (coul),

E_p = electric field near the collection electrode (volt/m),

a = particle radius (m),

μ = gas viscosity (kg/m-sec),

C = Cunningham correction factor, or slip correction factor[11] = $(1 + A'\lambda/a)$,

where A' = $1.257 + 0.400 \exp(-1.10\ a/\lambda)$, and

λ = mean free path of gas molecules (m).

In industrial precipitators, laminar flow never occurs and the effect of turbulent gas flow must be considered. The turbulence is due to the complex motion of the gas itself, electric wind effects of the corona, and transfer of momentum to the gas by the movement of the particles. Average gas flow velocities in most cases of practical interest are between 0.6 and 2.0 m/sec. Due to eddy formation, electric wind, and other possible effects, the instantaneous velocity of a small volume of gas surrounding a particle may reach peak values which are much higher than the average gas velocity. In contrast, migration velocities for particles smaller than 0.6 μm in diameter are usually less than 0.3 m/sec. Therefore, the motion of these smaller particles tends to be dominated by the turbulent motion of the gas stream. Under these conditions, the paths taken by the particles are random and the determination of the collection efficiency of a given particle becomes, in effect, the problem of determining the probability that a particle will enter a laminar boundary zone adjacent to the collection electrode in which capture is assured.

Using probability concepts and the statistical nature of the large number of particles in a precipitator, White[12] derived an expression for the collection efficiency in the form

$$\eta_m = 1 - \exp\left(-A_p w_p / Q\right) \quad , \qquad (2)$$

where η_m = collection fraction for a monodisperse aerosol,

A_p = collection area (m^2),

w_p = migration velocity near the collection electrode of the particles in the monodisperse aerosol (m/sec), and

Q = gas volume flow rate (m^3/sec).

The simplifying assumptions on which the derivation of equation (2) is based are:

(1) The gas is flowing in a turbulent pattern at a constant, mean forward-velocity.

(2) Turbulence is small scale (eddies are small compared to the dimensions of the duct), fully developed, and completely random.

(3) The particle migration velocity near the collecting surface is constant for all particles and is small compared with the average gas velocity.

(4) There is an absence of disturbing effects, such as particle reentrainment, back corona, particle agglomeration, or uneven corona.

Experimental data[13] under conditions which are consistent with the above assumptions demonstrate that equation (2) adequately describes the collection of monodisperse aerosols in an electrostatic precipitator under certain idealized conditions.

In industrial precipitators, the above assumptions are never completely satisfied but they can be approached closely. With proper design, the ratio of the standard deviation of the gas velocity distribution to the average gas velocity can be made to be 0.25 or less so that an essentially uniform, mean forward-velocity would exist. Although turbulence is not generally a completely random process, a theoretical determination of the degree of correlation between successive states of flow and between adjacent regions of the flow pattern is a difficult problem and simple descriptive equations do not presently exist for typical precipitator geometries. At the present, for purposes of modeling, it appears practical and plausible to assume that the turbulence is highly random. For particles larger than 10 μm diameter, the turbulence does not dominate the motion of these particles due to their relatively high migration velocities. Under these conditions, equation (2) would be expected to underpredict collection efficiencies. The practical effect in modeling precipitator performance will be slight, however, since even equation (2) predicts collection efficiencies greater than 99.6% for 10 μm diameter particles at relatively low values of current density and collection area [i.e., a current density of 10 nA/cm^2 and a collection area to volume flow ratio of 39.4 $m^2/(m^3/sec)$].

REMOVAL OF COLLECTED MATERIAL

In dry collection, the removal of the precipitated material from the collection plates and subsequent conveyance of the material away from the precipitator represent fundamental steps in the collection process. These steps are fundamental because collected material must be removed from the precipitator and because the buildup of excessively thick layers on the plates must be prevented in order to ensure optimum electrical operating conditions. Material which has been precipitated on the collection plates is usually dislodged by mechanical jarring or vibration of the plates, a process calling rapping. The dislodged material falls under the influence of gravity into hoppers located below the plates and is subsequently removed from the precipitator.

The effect of rapping on the collection process is determined primarily by the intensity and frequency of the force applied to the plates. Ideally, the rapping intensity must be large enough to remove a significant fraction of the collected material but not so large as to propel material back into the main gas stream. The rapping frequency must be adjusted so that a larger thickness which is easy to remove and does not significantly degrade the electrical conditions is reached between raps. In practice, the optimum rapping intensity and frequency must be determined by experimentation. With perfect rapping, the sheet of collected material would not reentrain, but would migrate down the collection plate in a stick-slip mode, sticking by the electrical holding forces and slipping when released by the rapping forces.

SECTION 5

LIMITING FACTORS AFFECTING PRECIPITATOR PERFORMANCE

ALLOWABLE VOLTAGE AND CURRENT DENSITY

The performance of a precipitator which has good mechanical and structural features will be determined primarily by the electrical operating conditions. Any limitations on applied voltage and current density will be reflected in the optimum collection efficiency which can be obtained. A precipitator should be operated at the highest useful values of applied voltage and current density for the following reasons:

(1) high applied voltages produce high electric fields;

(2) high electric fields produce high values of the saturation and limiting charge that a particle may obtain;

(3) high current densities produce high rates at which particles charge to the saturation or limiting values of charge;

(4) high current densities produce an increased electric field near the collection electrode due to the "ionic space charge" contribution to the field; and

(5) high values of electric field and particle charge produce high migration velocities and increased transport of particles to the collection electrode.

Electrical conditions in a precipitator are limited by either electrical breakdown of the gas in the interelectrode space or by electrical breakdown of the gas in the collected particulate layer. In a clean-gas, clean-plate environment, gas breakdown can originate at the collection electrode due to surface irregularities and edge effects which result in localized regions of high electric field. If the electric field in the interelectrode space is high enough, the gas breakdown will be evidenced by a spark which propagates across the interelectrode space. The operating applied voltage and current density will be limited by these sparking conditions.

If a particulate layer is deposited on the collection electrode, then the corona current must pass through the particulate layer to the grounded, collection electrode. The voltage drop (V_L) across the particulate layer is

$$V_L = j\rho' t \quad , \tag{3}$$

where j = current density (A/cm^2),

ρ' = resistivity of particulate layer (ohm-cm), and

t = thickness of the layer (cm).

The average electric field in the particulate layer (E_L) is given by

$$E_L = j\rho' . \tag{4}$$

The average electric field in the particulate layer can be increased to the point that the gas in the interstitial space breaks down electrically. This breakdown results from the acceleration of free electrons to ionization velocity to produce an avalanche condition similar to that at the corona electrode. When this breakdown occurs, one of two possible situations will ensue. If the electrical resistivity of the particulate layer is moderate (~ 0.1-1.0×10^{11} ohm-cm), then the applied voltage may be sufficiently high so that a spark will propagate across the interelectrode space. The rate of sparking for a given precipitator geometry will determine the operating electrical conditions in such a circumstance. If the electrical resistivity of the particulate layer is high ($>10^{11}$ ohm-cm), then the applied voltage may not be high enough to cause a spark to propagate across the interelectrode space. In this case, the particulate layer will be continuously broken down electrically and will discharge positive ions into the interelectrode space. This condition is called back corona. The effect of these positive ions is to reduce the amount of negative charge on a particle due to bipolar charging and reduce the electric field associated with the "ionic space charge". Both the magnitude of particle charge and rate of particle charging are affected by back corona. Useful precipitator current is therefore limited to values which occur prior to electrical breakdown whether the breakdown occurs as sparkover or back corona.

Field experience shows that current densities for cold side precipitators are limited to approximately 50-70 nA/cm^2 due to electrical breakdown of the gases in the interelectrode space. Consequently, this constitutes a current limit under conditions where breakdown of the particulate layer does not occur.

Electrical breakdown of the particulate layer has been studied extensively by Penney and Craig[14] and Pottinger[15] and can be influenced by many factors. Experimental measurements show that particulate layers experience electrical breakdown at average electric field strengths across the layers of approximately 5 kV/cm. Since it takes an electric field strength of approximately 30 kV/cm to cause electrical breakdown of air, the low breakdown strength of particulate layers suggests that high localized fields exist in the particulate layer and produce the breakdown of the gas in the layer. The presence of dielectric or conducting particles can cause localized regions of high electric field which constitute a negligible contribution to the average electric field across the layer. The size distribution of the collected particles also influences the electrical breakdown strength by changing the volume of interstices.[16] It has also been found that breakdown strength varies with particulate resistivity with the higher breakdown strength being associated with the higher resistivity.

METHODS FOR PREDICTING FLY ASH ELECTRICAL RESISTIVITY

Since the electrical resistivity has a pronounced effect on the electrostatic collectability of fly ash, it is desirable to have advanced knowledge regarding the magnitude of resistivity one might expect from a given coal. Obviously the best source of this information would be in situ resistivity measurements made during the burning of the subject coal in a commercial boiler. If the coal has not been used commercially, one has the option of burning the coal in a small scale pilot furnace and measuring the resistivity in situ or in the laboratory, or one can utilize one of the methods[17,18,19] for predicting fly ash resistivity.

These methods for predicting resistivity are based on correlations that have been established between resistivity and fly ash compositions for specific laboratory test conditions. The techniques leave much to be desired. First, although coal ash analyses can be used, the predictors are based on fly ash analyses. Second, the predictors do not take into account the effect of environmental variations. Recent research[20] has led to a predictive technique which utilizes the chemical composition of a coal ash and the stoichiometrically calculated flue gas.

NONIDEAL EFFECTS

The nonidealities which exist in full-scale electrostatic precipitators will reduce the ideal collection efficiency that may be achieved with a given specific collection area. The nonideal effects of major importance are (1) nonuniform gas velocity distribution, (2) gas sneakage, and (3) particle reentrainment. These nonideal effects must be minimized by proper design and optimization of a precipitator in order to avoid serious degradation in performance.

Nonuniform Gas Velocity Distribution

Uniform, low-turbulence gas flow is essential for optimum precipitator performance. Nonuniform gas flow through a precipitator lowers performance due to two effects. First, due to the exponential nature of the collection mechanism, it can be shown mathematically that uneven treatment of the gas lowers collection efficiency in the high velocity zones to an extent not compensated for in the low velocity zones. Secondly, high velocity regions near collection plates and in hopper areas can sweep particles back into the main gas stream.

Although it is known that a poor gas velocity distribution results in reduced collection efficiency, it is difficult to formulate a mathematical description for gas flow quality. White[21] discusses nonuniform gas flow and suggests corrective actions. Preszler and Lajos[22] assign a figure-of-merit based upon the relative kinetic energy of the actual velocity distribution compared to the kinetic energy of the average velocity. This figure-of-merit provides a measure of how difficult it may be to rectify the velocity distribution but not necessarily a measure of how much the precipitator performance would be degraded. At the inlet of a precipitator, a value of 0.25 or less for the ratio of the standard deviation of the gas velocity distribution to the average gas velocity is generally recommended. However, it must be noted that the gas velocity distribution can change significantly throughout the length of a precipitator and, depending upon the design of the precipitator and the manner in which it is interfaced with other plant equipment, the gas velocity distribution may improve or degrade.

Gas Sneakage

Gas sneakage occurs when gas bypasses the electrified regions of an electrostatic precipitator by flowing through the hoppers or through the high voltage insulation space. Gas sneakage can be reduced by the use of frequent baffles which force the gas to return to the main gas passages between the collection plates. If there were no baffles, the percent gas sneakage would establish the maximum possible collection efficiency because it would be the percent volume having zero collection efficiency. With baffles, the sneakage gas remixes with part of the main gas flow and then another fraction of the main gas flow re-bypasses in the next unbaffled region. The upper limit on collection efficiency due to gas sneakage will therefore depend on the amount of sneakage gas per baffled section, the degree of remixing, and the number of baffled sections. Gas sneakage becomes increasingly important for precipitators designed for high collection efficiencies where only a small amount of gas sneakage per section can result in a severe limitation on collection efficiency.

Particle Reentrainment

Particle reentrainment occurs when collected material reenters the main gas stream. This can be caused by several different effects and, in certain cases, can severely reduce the collection efficiency of a precipitator. Causes of particle reentrainment include (1) rapping which propels collected material into the interelectrode space, (2) the action of the flowing gas stream on the collected particulate layer, (3) sweepage of material from hoppers due to poor gas flow conditions, air inleakage into the hoppers, or the boiling effect of rapped material falling into the hoppers, and (4) excessive sparking which dislodges collected material by electrical impulses and disruptions in the current which is necessary to provide the electrical force which holds the material to the collection plates.

Recent studies[23,24] have been made to determine the effect of particle reentrainment on precipitator performance. In studies where the rappers were not employed, real-time measurements of outlet emissions at some installations showed that significant reentrainment of mass was occurring due to factors other than rapping. These same studies also showed that for high-efficiency, full-scale precipitators approximately 30-85% of the outlet particulate emissions could be attributed to rapping reentrainment. The results of these studies show that particle reentrainment, especially rapping reentrainment, is a significant factor in limiting precipitator performance.

SECTION 6

DESCRIPTION OF THE MATHEMATICAL MODEL

IDEAL CALCULATION OF PARTICLE COLLECTION EFFICIENCY

The mathematical model of electrostatic precipitation is based on the exponential-type relationship given in equation (2). This equation was derived subject to several assumptions which have been stated earlier. In order to use the equation it is necessary to structure the mathematical model such that the assumptions are not violated. As discussed earlier, the assumptions are never completely satisfied in an industrial precipitator but they can be approached closely.

The assumption that the particle migration velocity near the collection surface is constant for all particles has the most significant effect on the structure of the model. This assumption implies two things:

(1) The particles are all of the same diameter.

(2) The electrical conditions are constant.

Because the particles entering a precipitator are not all of the same diameter, the assumption of uniform particle diameters creates a problem. This problem is dealt with in the model by performing all calculations for single diameter particles and then summing the results to determine the effect of the electrostatic precipitation process on the entire particle size distribution.

Because the electrical conditions change along the length of a precipitator, the assumption of constant electrical conditions creates a problem. This problem is dealt with in the model by dividing the precipitator into small length increments. These length increments can be made small enough that the electrical conditions remain essentially constant over the increment. The number of particles of a given diameter which are collected in the different length increments are summed to determine the collection efficiency of particles of a single diameter over the entire length of the precipitator.

In summary, a precipitator is divided into essentially many small precipitators in series. Equation (2) is valid in each of these small precipitators for particles of a given diameter. A large majority of the time used in the computer program which performs the calculations in the model is devoted to calculating the values of quantities needed to determine the migration velocity for each particle diameter in each length increment.

The collection fraction, $\eta_{i,j}$, for the i-th particle size in the j-th increment of length of the precipitator is mathematically represented in the form

$$\eta_{i,j} = 1 - \exp\left(-w_{i,j} A_j/Q\right) \quad , \tag{5}$$

where $w_{i,j}$ (m/sec) is the migration velocity of the i-th particle size in the j-th increment of length and A_j (m^2) is the collection plate area in the j-th increment of length.

The collection fraction (fractional efficiency) η_i for a given particle size over the entire length of the precipitator is determined from

$$\eta_i = \frac{\sum_j \eta_{i,j} N_{i,j}}{N_{i,1}} \quad , \tag{6}$$

where $N_{i,j}$ is the number of particles of the i-th particle size per cubic meter of gas entering the j-th increment. The quantity $N_{i,j}$ can be written in the form

$$N_{i,j} = N_{i,j-1} \exp\left(-w_{i,j-1} A_{j-1}/Q\right) \quad , \tag{7}$$

where $N_{i,1} = N_{i,0}$, the number of particles of the i-th particle size per cubic meter of gas in the inlet size distribution which is expressed in the form of a histogram.

The overall mass collection efficiency η for the entire polydisperse aerosol is obtained from

$$\eta = \sum_i \eta_i P_i \quad , \tag{8}$$

where P_i is the percentage by mass of the i-th particle size in the inlet size distribution.

In order to determine the migration velocities for use in equation (5), the electrical conditions and the particle charging process in a precipitator must be modeled.

Calculation of Electrical Conditions

If the operating voltage and current are known and a voltage-current curve is not desired, then the electric potential and electric field distributions are determined by using a relaxation technique described by Leutert and Böhlen.[1,25] In this numerical technique, the appropriate partial differential equations which describe the electrodynamic field are solved simultaneously under boundary conditions existing in a wire-plate geometry. The equations which must be solved are written in discrete form in two dimensions as

$$\frac{\Delta^2 V}{\Delta x^2} + \frac{\Delta^2 V}{\Delta y^2} = -\frac{\rho}{\varepsilon_0} \quad \text{, and} \tag{9}$$

$$\rho^2 = \varepsilon_0 \left(\frac{\Delta V}{\Delta x}\frac{\Delta \rho}{\Delta x} + \frac{\Delta V}{\Delta y}\frac{\Delta \rho}{\Delta y}\right) + \frac{\varepsilon_0 \rho}{b_e}\left(\frac{\Delta V}{\Delta x}\frac{\Delta b_e}{\Delta x} + \frac{\Delta V}{\Delta y}\frac{\Delta b_e}{\Delta y}\right) \quad , \tag{10}$$

where ρ = space charge density (coul/m^3),

b_e = effective charge carrier mobility (m^2/V-sec),

y = coordinate parallel to gas flow from wire-to-wire (m),

x = coordinate perpendicular to gas flow from wire-to-plate (m), and

ε_0 = permittivity of free space (coul/N-m^2).

In order to find the solutions for V and ρ from equations (9) and (10), the known boundary conditions on applied voltage and current are held fixed while the space charge density at the wire is adjusted until all the boundary conditions are satisfied. For each choice of space charge density at the wire, the procedure iterates on a grid of electric potential and space charge density until convergence is obtained and then checks to see if the boundary condition on the average current density at the plate is met by using the expression

$$J_p = \left(b_e \sum_{i=1}^{N} \rho_{pi} \, E_{pi}\right)/N \quad , \tag{11}$$

where J_p = average current density at the plate (A/m^2),

b_e = effective charge carrier mobility (m^2/V-sec),

ρ_{pi} = space charge densities for points on the plate ($coul/m^3$),

E_{pi} = electric field strengths for points on the plate (V/m), and

N = number of grid points in the direction of gas flow.

If the boundary condition on the average current density at the plate is not met, then the space charge density at the wire is adjusted and the iteration procedure is repeated.

If the operating voltage and current are unknown or if a voltage-current curve is desired, then the voltage-current characteristic for a wire-plate geometry is determined by using the technique described by McDonald et al.[26] In this technique, the electric potential and electric field distributions are determined for each point on the voltage-current curve. Equations (9) and (10) are solved simultaneously using the same mathematical procedure employed by Leutert and Böhlen but an alternate set of boundary conditions is imposed. The space charge density in the region of ionization near the discharge electrode is calculated from an arbitrarily chosen value of average current density at the plate. The space charge density near the wire and the average current density at the plate provide boundary conditions which are held fixed while the electric potential at the wire is adjusted until simultaneous solutions are found to equations (9) and (10) which satisfy all the boundary conditions.

Calculation of Particle Charge

Particle charge is calculated from a unipolar, ionic-charging theory formulated by Smith and McDonald.[27] In this theory, particle charge is predicted as a function of particle diameter, exposure time, and electrical conditions. The charging equation is derived based on concepts from kinetic theory and determines the charging rate in terms of the probability of collisions between particles and ions. The theory accounts simultaneously for the effects of field and thermal charging and accounts for the effects of the applied electric field on the thermal charging process. According to this theory, the charging rate is given by

$$
\begin{aligned}
\frac{dq}{dt} = {} & \frac{N_0 ebq_s}{4\varepsilon_0}\left(1 - \frac{q}{q_s}\right)^2 \\
& + \frac{\pi a^2 \tilde{v} N_0 e}{2} \int_{\theta_0}^{\pi/2} \exp\left[\left(\frac{qe(r_0-a)}{4\pi\varepsilon_0 kTar_0}\right.\right. \\
& \left.\left. + \frac{[3ar_0{}^2 - r_0{}^3(K+2) + a^3(K-1)]eE_0\cos\theta}{kTr_0{}^2\ (K+2)}\right)\right] \sin\theta d\theta \\
& + \frac{\pi a^2 \tilde{v} N_0 e}{2} \exp\left(-qe/4\pi\varepsilon_0 akT\right) \quad , \qquad (12)
\end{aligned}
$$

where $q_s = 4\pi\varepsilon_0 E_0 a^2 \left(1 + 2\,\frac{K-1}{K+2}\right)$, (13)

$\theta_0 = \arccos\,(q/q_s)$, (14)

and q = instantaneous charge on the particle (coul),

q_s = saturation charge due to field charging (coul),

θ = azimuthal angle in a spherical coordinate system with origin at the center of the particle (radians),

θ_0 = maximum azimuthal angle for which electric field lines enter the particle (radians),

N_0 = free ion density (m^{-3}),

e = electronic charge (coul),

ε_0 = permittivity of free space (coul/V-m),

E_0 = average electric field between the electrodes (V/m),

b = ion mobility (m^2/V-sec),

$\tilde{v}$ = mean thermal speed of ions (m/sec),

a = particle radius (m),

k = Boltzmann's constant (J/°K),

T = absolute temperature (°K),

t = time (sec),

K = dielectric constant of the particle, and

r_0 = radial distance along θ at which the radial component of the total electric field is zero (m).

For large particles and high applied electric fields, the theory predicts essentially the same charging rate as the classical field charging equation. For low applied electric fields, the charging equation reduces to the classical thermal equation.

Equation (12) can be solved on a computer by simple numerical techniques. The integral on the right-hand side of equation (12) is evaluated using Gaussian quadratures and the charge as a function of time is determined by using the quartic Runge-Kutta method.

In cases where the use of computer time is an important consideration, the computer model for electrostatic precipitation allows for considerable savings in computer time by providing the option of using an analytical expression for charge as a function of time. This expression is given by

$$\begin{aligned} q &= q_D + q_F \\ &= \left(\frac{4\pi\varepsilon_0 akT}{e}\right) \ln \left[\left(\frac{e^2 a\tilde{v}N_0}{4\varepsilon_0 kT}\right)\left(t_f - t_i\right) + \mathrm{Exp}\left(\frac{q_i e}{4\pi\varepsilon_0 akT}\right)\right] \\ &\quad + q_s \left[\frac{\left(\frac{N_0 be}{4\varepsilon_0}\right)\left(t_f - t_i\right) + \frac{1}{(1-q_i/q_s)} - 1}{\left(\frac{N_0 be}{4\varepsilon_0}\right)\left(t_f - t_i\right) + \frac{1}{(1-q_i/q_s)}}\right] \quad , \qquad (15) \end{aligned}$$

where q_D = charge predicted from classical diffusion charging theory (coul),

q_F = charge predicted from classical field charging theory (coul),

t_i = initial time for charging under a fixed set of conditions (sec),

t_f = final time for charging under a fixed set of conditions (sec),

q_i = charge on the particle at t_i (coul),

and all other symbols are as defined previously.

This equation represents the sum of the charges from classical field and diffusion charging theories. In principle, the sum of the charging rates should be added to be physically meaningful; however, fortuitously, equation (15) yields a reasonable prediction of particle charge for particles in the size range 0.09-1.4 μm in diameter.[28] The forms of q_D and q_F used in equation (15) reflect the fact that N_0 and E_0 change along the length of a precipitator and, in the model, are assumed to remain fixed only over each incremental length.

Calculation of Space Charge Effects

In the calculation of the electrical conditions, it is assumed that the motion of all the charge carriers can, on the average, be described by a single "effective mobility". The presence of particles in the flue gas will cause a reduction in the "effective mobility" because the particles, which acquire charge from the ions and are much less mobile than ions, must carry part of the total current.[1,29,30] When the electrical conditions are calculated by using measured values of applied voltage and current density, the "effective mobility" is determined from[1,29]

$$b_e = b' \left(\frac{j_t}{200\, j_p + j_t} \right) , \qquad (16)$$

where b_e = effective mobility for ions and particles (m^2/V-sec),

b' = effective ion mobility (m^2/V-sec),

j_t = total current density at the plate (A/m^2), and

j_p = particulate current density at the plate (A/m^2).

If the electrical conditions are calculated by generating a voltage-current curve, then the model employs a different method for determining the effects of space charge. This method is discussed in detail in Appendix A. In this method, the precipitator is divided into successive length increments which are equal to the wire-to-wire spacing. Each of these increments is divided into several subincrements. The first calculation in the procedure involves the determination of a clean-gas, voltage-current curve which terminates at some specified value of applied voltage. At the specified applied voltage, the average electric field and ion density are calculated in each subincrement. This allows for the nonuniformity of the electric field and current density distributions to be taken into account.

As initially uncharged particles enter and proceed through the precipitator, the mechanisms of particle charging and particle collection are considered in each subincrement. In each subincrement, the average ion density, average particulate density, weighted particulate mobility, and effective mobility due to both ions and particles are determined. At the end of each increment, the effective mobilities for the subincrements are averaged in order to obtain an average effective mobility for the increment. Then, for the specified value of applied voltage, the average effective mobility is used to determine the reduced current for the increment by either calculating a new voltage-current curve or using an approximation which is discussed in Appendix A. This method provides good estimates of reduced current due to the presence of particles. However, it does not have the capability of predicting the redistribution of the electric field due to the presence of particles.

METHODS FOR ESTIMATING NONIDEAL EFFECTS

Since the model is structured around an exponential-type equation for individual particle sizes, it is convenient to represent the effect of the nonidealities in the model as correction factors which apply to the exponential argument. These correction factors are used as divisors for the ideally-calculated effective migration velocities.

Since four types of migration velocities will be referred to in the following sections, it is important to define the terminology which will be used. The *migration velocity w* is a quantity which is calculated from fundamental principles and applies only to a given length increment as used in the model. This quantity represents the actual drift velocity of a particle toward the collection electrode in the region near the collection electrode. The *effective or length-averaged migration velocity w_e* is a quantity which is calculated from fundamental principles but it applies to the entire length of the precipitator. This quantity is obtained by replacing w_p in equation (2) by w_e and determining a single value of w_e which is necessary to produce the same collection efficiency over the entire length of the precipitator that is obtained from the values of w. The apparent effective migration velocity w_e' is a quantity which is obtained from making an empirical correction (or corrections) to the effective migration velocity w_e. This quantity bears no relationship to the actual migration velocities in the region of space adjacent to the collection electrode and has no physical interpretation. The quantities w, w_e, and w_e' apply to particles of a given diameter. The precipitation rate parameter w_{pr} is a quantity which provides a measure of how well the entire mass which enters the precipitator will be collected. This quantity is obtained by replacing w_p in equation (2) by w_{pr} and determining a single value of w_{pr} which is necessary to produce the same overall mass collection efficiency that is obtained from the collection efficiencies for all particle diameters, as determined by the values of w_e or w_e', and the inlet particle size distribution.

Calculation of Effect of Nonuniform Velocity Distribution

It is possible to develop an approach to estimating the degradation of performance due to a nonuniform velocity distribution based upon the velocity distribution, the ideal collection efficiencies, and the exponential-type collection equation.[1] In this approach, it is assumed that equation (2) applies to each particle size with a known effective migration velocity and that the specific collecting area and size of the precipitator are fixed.

For any practical velocity distribution and efficiency, the mean penetration obtained by summation over the point values of velocity will be higher than the penetration calculated from the average velocity. If an effective migration velocity for a given particle size is calculated based upon the mean penetration and equation (2), the resulting effective migration velocity will have a value lower than the value necessary to obtain the same mean penetration from a summation of point values of penetration. The ratio of the effective migration velocity determined by the summation of point values of penetration to that determined by equation (2) is a numerical measure of the performance degradation caused by a nonuniform velocity distribution. An expression for this ratio may be obtained by setting the penetration based on the average velocity equal to the corrected penetration obtained from a summation of the point values of penetration and solving for the required correction factor, which will be a divisor for the effective migration velocity obtained from equation (2).

Whether the correction factor obtained from the above procedure correlates reasonably well with statistical measures of velocity nonuniformity is yet to be established. A limited number of traverse calculations which have been performed seem to indicate a correlation between the correction factor and the normalized standard deviation of the velocity traverse. Based upon a pilot plant study,[22] the following empirical relationship between the correction factors F_i, the normalized standard deviation of the velocity distribution σ_g, and the ideal collection fractions η_i for the i-th particle size under consideration has been obtained:[1]

$$F_i = 1 + 0.766\ \eta_i \sigma_g^{1.786} + 0.0755\ \sigma_g \ln (1/1-\eta_i). \qquad (17)$$

In simulating the performance of a particular precipitator, the preferred procedure would be to obtain the relationship $[F_i = F_i\ (\eta_i, \sigma_g)]$ between F_i, η_i, and σ_g for the conditions to be simulated from a velocity traverse at the entrance to the precipitator. If this cannot be done, equation (17) can be used, but only in the sense of obtaining a rough estimate of the effects of a given nonuniform velocity distribution.

Calculation of Effect of Gas Sneakage

If the simplifying assumption is made that perfect mixing occurs following each baffled section, then an expression for the penetration P_{N_S} of a given particle size from the last baffled section which is corrected for gas sneakage can be derived[1] in the form

$$P_{N_S} = [S + (1-S)(1-\eta_i)^{1/N_s}]^{N_s} \quad , \qquad (18)$$

where S is the fractional amount of gas sneakage per baffled section and N_s is the number of baffled sections. Estimations based on equation (18) indicate that, for high efficiencies, the number of baffled sections should be at least four and the amount of sneakage should be held to a low percentage. With a high percentage of sneakage, even a large number of baffled sections fail to help significantly.

Gas sneakage factors B_i can be defined in the form of divisors for the effective, or length-averaged, migration velocities in the exponential argument of equation (2). The factors B_i are obtained by taking the ratio of the effective migration velocities $w_{e,i}$ under ideal conditions to the apparent effective migration velocities $w'_{e,i}$ under conditions of gas sneakage so that

$$B_i = \frac{w_{e,i}}{w'_{e,i}} = \frac{\ln (1-\eta_i)}{\ln P_{N_S}} = \frac{\ln (1-\eta_i)}{N_s \ln [S + (1-S)(1-\eta_i)^{1/N_s}]} , \qquad (19)$$

where the subscript i refers to the different particle diameters.

The foregoing estimation of the effects of gas sneakage is a simplification in that the sneakage gas passing the baffles will not necessarily mix perfectly with the main gas flow and the flow pattern of the gas in the bypass zones will not be uniform and constant. Equation (18) has been formulated to help in designing and analyzing precipitators by establishing the order of magnitude of the problem. Considerable experimental data will be required in order to evaluate the method and to establish numerical values of actual sneakage rates.

Calculation of Effect of Reentrainment Without Rapping

Although it is difficult to quantify the complex mechanisms associated with particle reentrainment due to (1) the action of the flowing gas stream on the collected particulate layer, (2) sweepage of particles from hoppers caused by poor gas flow conditions or air inleakage into the hoppers, and (3) excessive sparking, the effect of these nonideal conditions on precipitator performance can be estimated if some simplifying assumptions are made. If it is assumed that a fixed fraction of the collected material of a given particle size is reentrained and that the fraction does not vary with length through the precipitator, an expression can be derived which is identical in form to that obtained for gas sneakage:[1]

$$P_{N_R} = [R + (1-R)1-\eta_i)^{1/N_R}]^{N_R} , \qquad (20)$$

where P_{N_R} is the penetration of a given particle size corrected for reentrainment, R is the fraction of material reentrained, and N_R is the number of stages over which reentrainment is assumed to occur.

Since equations (18) and (20) are of the same form, the effect of particle reentrainment without rapping can be expected to be similar to the effect of gas sneakage, provided that a constant fraction of the collected material is reentrained in each stage. It is doubtful that such a condition exists, since the gas flow pattern changes throughout the precipitator and different holding forces and spark rates exist in different electrical sections. However, until detailed studies are made to quantify the losses in collection efficiency as a function of particle size for these types of reentrainment, equation (20) provides a means of estimating the effect of particle reentrainment without rapping on precipitator performance.

Since the equation which is obtained for calculating the correction factors for particle reentrainment without rapping is of the same form as that obtained for calculating the correction factors for gas sneakage, only equation (19) is used in the model. Thus, only a value of S is used as input data for the model. However, the value of S represents the combined effects of the fractional amount of gas sneakage per baffled section and the fractional amount of collected material which is reentrained per baffled section without rapping.

No-Rap Calculations

The combined nonideal effects of nonuniform gas velocity distribution, gas sneakage, and particle reentrainment without rapping are taken into account by reducing the ideally calculated effective migration velocities $w_{e,i}$ by the correction factors F_i and B_i. Apparent effective migration velocities $w'_{e,i}$ are determined from

$$w'_{e,i} = \frac{w_{e,i}}{F_i \cdot B_i} \quad , \qquad (21)$$

where the subscript i refers to the different particle diameters. Corrected fractional collection efficiencies are calculated using equation (2) and the values of the $w'_{e,i}$.

The apparent effective migration velocities and corresponding collection efficiencies obtained from equation (21) may be referred to as "no-rap" migration velocities and collection efficiencies. These quantities are of practical interest because they can be measured by turning the rappers off, whereas ideal quantities can never be truly measured.

Calculation of Effect of Rapping Reentrainment

The loss in collection efficiency due to rapping reentrainment may be calculated in either of two ways. The first is the empirical correction to the ESP effluent which was introduced in Revision 1 of the ESP model.[2] A discussion of this calculation is presented below. The second method involves the reintroduction of a fraction of the collected dust into the gas flow for recollection. This method of calculating the effects of rapping reentrainment dynamically is described following the discussion of the empirical method.

An empirical approach to representing the effects of rapping reentrainment has been developed based on studies performed as part of a program sponsored by the Electric Power Research Institute.[23] In these studies, outlet mass loadings and particle size distributions were measured both with and without rapping losses for six full-scale precipitators collecting fly ash. Based on these data, outlet mass loadings and particle size distributions which can be attributed to rapping were obtained.

The rapping emissions obtained from the measurements on the six precipitators are graphed in Figure 4 as a function of the amount of dust calculated to have been removed by the last electrical section. The dust removal in the last electrical section was approximated by

$$\eta'/\text{section} = 1-\exp(-X'/N_E) \quad , \tag{22}$$

where $X' = -\ln(1-\eta_0)$, (23)

η_0 = overall mass collection fraction determined from mass train measurements under normal operating conditions, and

N_E = number of electrical sections in series.

These data suggest a correlation between rapping losses and particulate collection rate in the last electrical section. Data for the two hot-side installations (4 and 6) which were tested show higher rapping losses than for the cold-side units. This would be expected due to reduced dust adhesivity at higher temperatures. Data 2a and 2b are for a cold-side unit operating at normal and approximately one-half normal current density, respectively. The decrease in current density at installation 2 resulted in a significant increase in rapping emissions due to the increased mass collected in the last field and smaller electrical holding force for the same rapping intensity.

The simple exponential relationships

$$y_1 = (0.155)x^{0.905} \tag{24}$$

and

$$y_2 = (0.618)x^{0.894} \tag{25}$$

can be used for interpolation purposes in determining the rapping emissions (mg/DSCM) for a given calculated mass removed by the last field (mg/DSCM) for cold- and hot-side precipitators, respectively. In constructing Figure 4, the calculated mass removed in the last field was determined by using the measured overall mass collection efficiency during normal operation of the precipitator. This was done because complete traverses were made by the mass trains during the normal tests whereas this was not the case for the measurements made during the no-rap tests. In

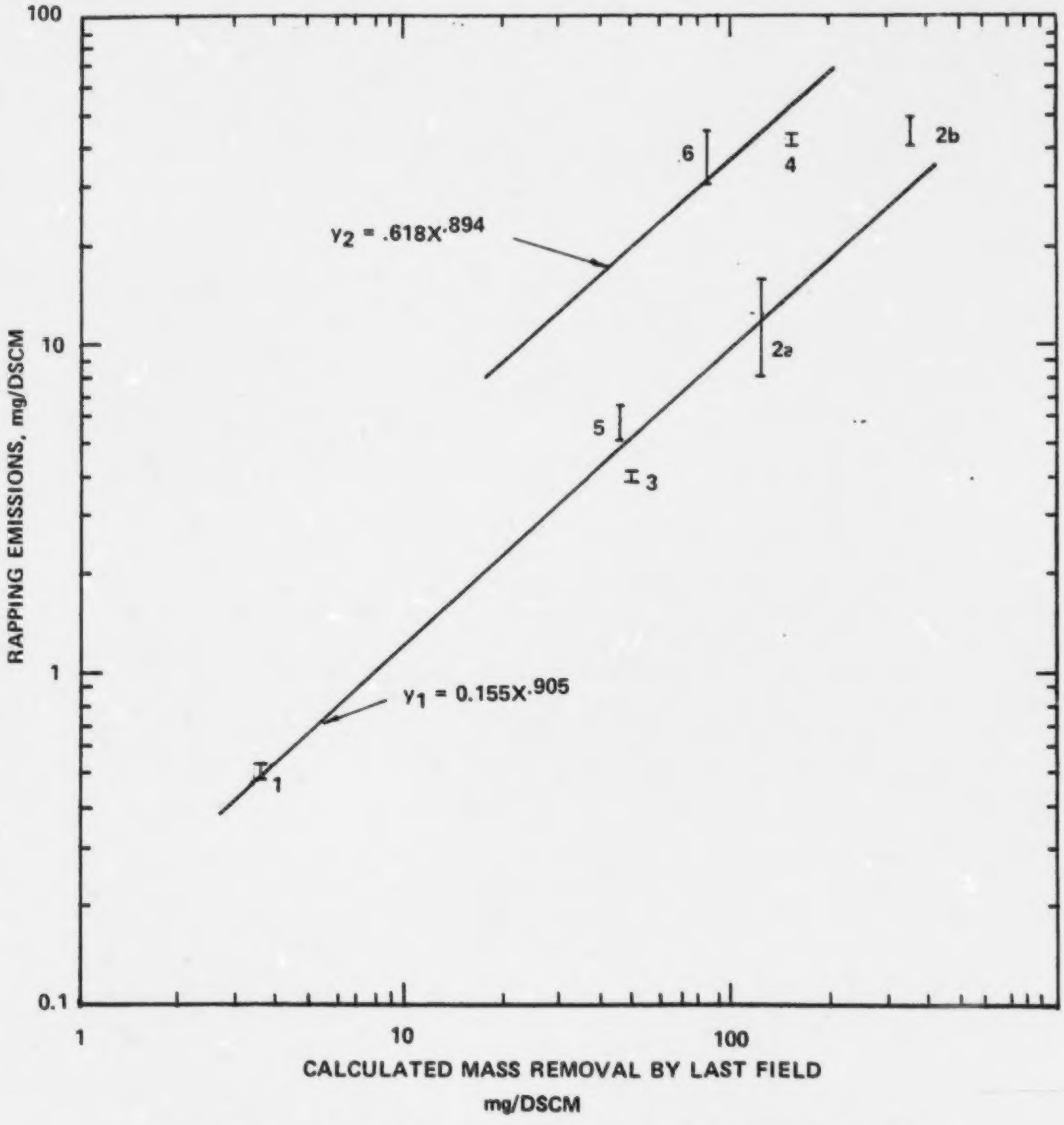


Figure 4. Measured rapping emissions versus calculated particulate removal by last electrical section. These curves are a result of work sponsored by the Electric Power Research Institute.

principle, the no-rap efficiencies should be used to calculate the mass removed in the last field and this is what is done in the mathematical model. Obviously, the limited amount of data obtained thus far is not sufficient to validate in general the approach presented here. However, this approach gives reasonable agreement with the existing data and offers a quantitative method for estimating rapping losses.

The apparent size distribution of emissions attributable to rapping at each installation was obtained by subtracting the cumulative distributions during non-rapping periods from those with rappers in operation, and dividing by the total emissions (based on impactor measurements) resulting from rapping in order to obtain a cumulative percent distribution. Figure 5 contains the results of these calculations. Although the data indicate considerable scatter, an average particle size distribution has been constructed in Figure 6 for use in modeling rapping puffs. In the mathematical model, the data in Figure 6 are approximated by a log-normal distribution with a mass median diameter of 6.0 μm and a geometric standard deviation of 2.5.

In summary, for the empirical rapping calculation, the mathematical model determines a "rapping puff" by using either equation (24) or (25) to obtain the outlet mass loading due to rapping and by using a log-normal approximation to the data in Figure 6 to represent the particle size distribution of the outlet mass loading due to rapping. This "rapping puff" is added to the "no-rap" outlet emissions to obtain the total outlet emissions as a function of mass loading and particle size distribution. Then, the model generates migration velocity, collection efficiency, penetration, and $\Delta M/\Delta \log D$ (rate of change of mass over a given size interval) as a function of particle diameter for the "no-rap", "rapping puff" and "no-rap" plus "rapping puff" outlet emissions.

In the dynamic calculation of rapping reentrainment, the effects of rapping are determined by a different process. The first step in this process is to perform the ideal efficiency calculation to determine the growth rate of the deposited dust layer. From this information, the dust layer thickness on the collection plates at the time of the rap is calculated for each increment of precipitator length. When the rap occurs, the duct layer thickness on the length increments which are rapped is set to zero as the collected dust layer is dislodged. The fraction of the removed dust layer which gets reentrained is fit to a log-normal size distribution in preparation for reintroduction into the gas flow. At this point, the ideal collection efficiency calculation is performed again with the reentrained dust being added to the dust already present in the gas flow. The addition of reentrained dust occurs immediately following the precipitator increment from which the dust was rapped. From this point, the reentrained dust is subject to the same collection processes as the other dust particles present in the gas flow.

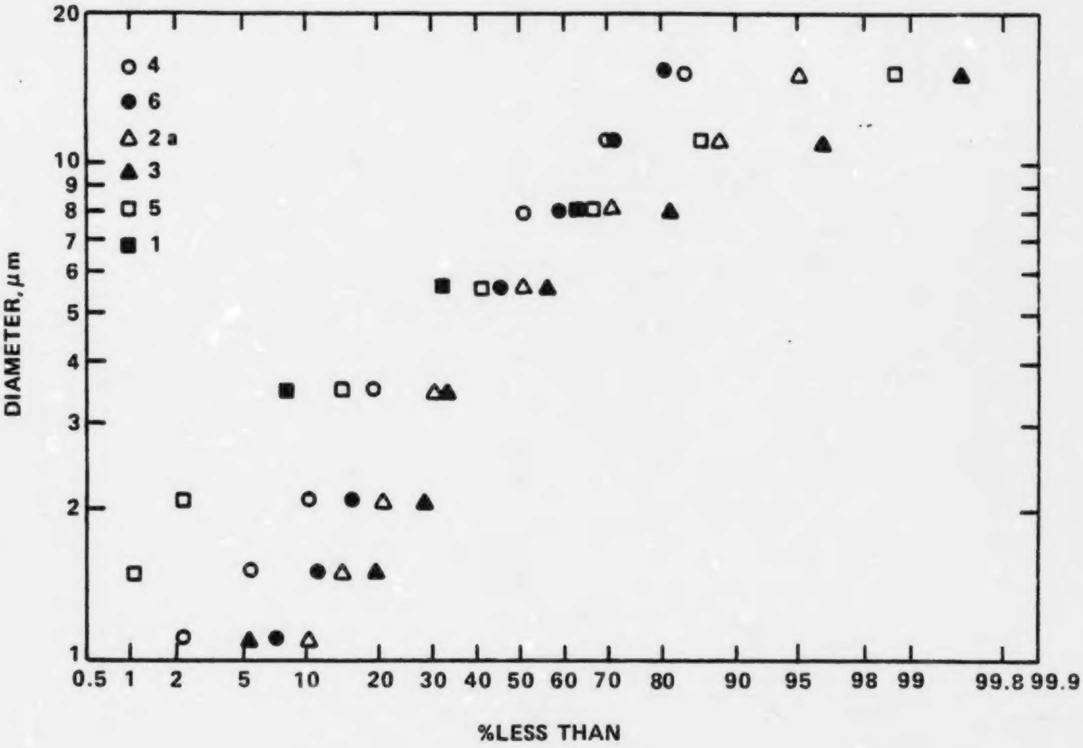


Figure 5. Apparent rapping puff size distribution for six full-scale precipitators. These data are a result of work sponsored by the Electric Power Research Institute.

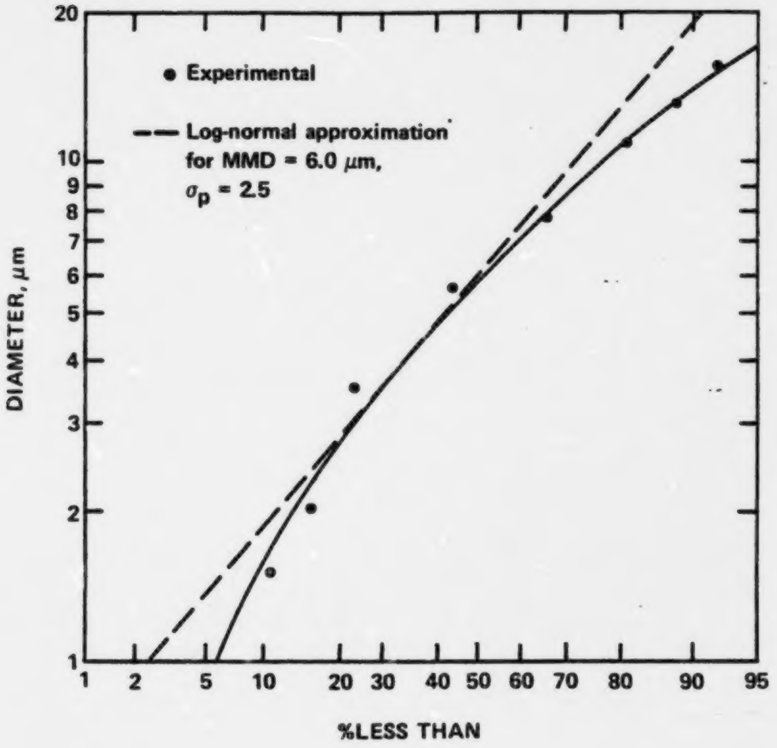


Figure 6. Average rapping puff size distribution for six full-scale precipitators. These data are a result of work sponsored by the Electric Power Research Institute.

Two assumptions pertain to this process. The first is that the amount and size distribution of the reentrained dust are known. In practice, this data may not be available and it may be necessary to estimate these quantities. The second assumption is that the reentrained dust particles are instantaneously recharged to the charge value that the same size particles in the regular flow have at that point in the ESP. This is an approximation made to simplify the calculation. In the actual process, the charges on these particles, and therefore the rates at which they recharge, are unknown.

The two methods of calculating the loss in collection efficiency due to rapping reentrainment have different requirements and yield different results. The only input data required by the empirical calculation is whether the ESP is a hot- or cold-side unit, although particle size distribution data may be read in if it is available. This routine calculates the average ESP effluent particle statistics resulting from an average rapping process. The empirical calculation adds very little additional computer time to the ideal efficiency calculation and yields reasonably good time-averaged numbers for full-scale precipitators. No data on individual rapping puffs can be obtained from this calculation.

The dynamic rapping procedure is a much more flexible approach to the rapping calculation in that each rap in the rapping scheme is examined at the time that it occurs. This allows variation of the rapping scheme for optimization of the rapping process. The input data requirements for this process includes the time of each rap, the fraction of the dislodged dust layer that gets reentrained from each rap, the particle size distribution of this reentrained dust and the time interval during which the dust is reentrained (i.e., the duration of the dust cloud resulting from the rap). The disadvantages of the dynamic rapping calculation are that much of the required input data may be unknown and will have to be estimated and that the computer time needed for this calculation is much greater than for the empirical correction. Neither rapping calculation includes the effects of the collected dust layer on the electric fields in the ESP, the recharging of the reentrained particles, or their effect on the space charge. Also omitted are calculations of the forces required to dislodge the dust from the plates.

EMPIRICAL CORRECTIONS TO NO-RAP MIGRATION VELOCITIES

Comparisons of measured apparent effective migration velocities for full-scale precipitators under "no-rap" conditions with those predicted by the model indicate that the field-measured values exceed the theoretically projected values (in the absence of back corona, excessive sparking, or severe mechanical problems) in the smaller size range. Based on these comparisons, a size-dependent correction factor has been constructed and incorporated into the model.[23] This correction factor is shown in Figure 7.

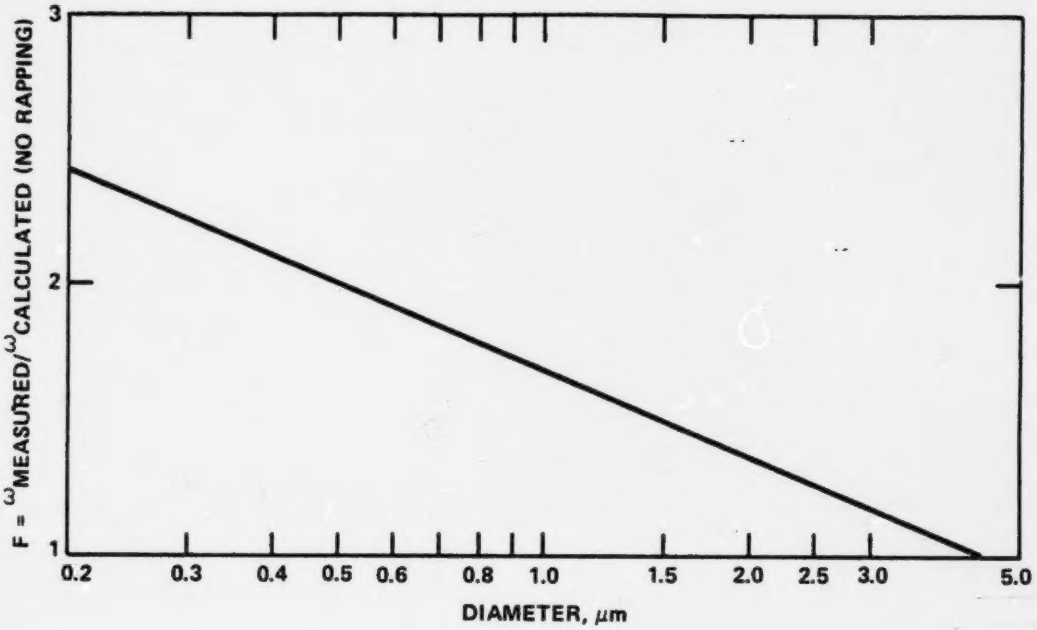


Figure 7. Empirical correction factors for the "no-rap" migration velocities calculated from the mathematical model. This work was sponsored by the Electric Power Research Institute.

The empirical correction factor accounts for those effects which enhance particle collection efficiency but are not included in the present model. These effects include particle charging near corona wires, particle charging by free electrons, particle concentration gradients, and flow field phenomena.

CALCULATION OF PLUME OPACITY

The reduction in the transmission of light passing through suspended particles occurs by scattering and absorption by these particles. The degree of reduction is a function of particle size, concentration, composition, and the optical path through the aerosol. For particles with diameters greater than about 1 μm, the extinction of light is essentially determined by the total projected area of the aerosol particles. For smaller sizes, particle composition becomes important. Consequently, for general applications, the calculation of opacity must be performed using a mathematical solution to Maxwell's equations. The theory used in this development is that of Gustav Mie[31] which gives, among other parameters, the extinction efficiency, Q_{ext}, in terms of the particle refractive index, n, and size parameter $\pi D/\lambda$ for isotropic homogeneous spheres. D and λ are particle diameter and the wavelength of the light beam, respectively. The extinction efficiency represents the effective projected area of a particle for removing light from a light beam compared to its geometrical projected area. This is related to opacity by

$$\text{Opacity} = 1-\exp(-EL) = 1-\exp(-NAQ_{ext}L), \qquad (26)$$

where

E = Extinction coefficient (m^{-1}),

L = Pathlength of the light beam (m),

N = Particle concentration (number/m^3), and

A = Particle projected area (m^2).

Figure 8 shows the extinction efficiency as a function of the particle size parameter for four complex refractive indices. Curves (b) and (d) represent the extinction efficiency for indices of refraction of 1.5 and 1.5-0.1 i, which are the default values of index of refraction which are used in the opacity calculation unless other values are supplied.

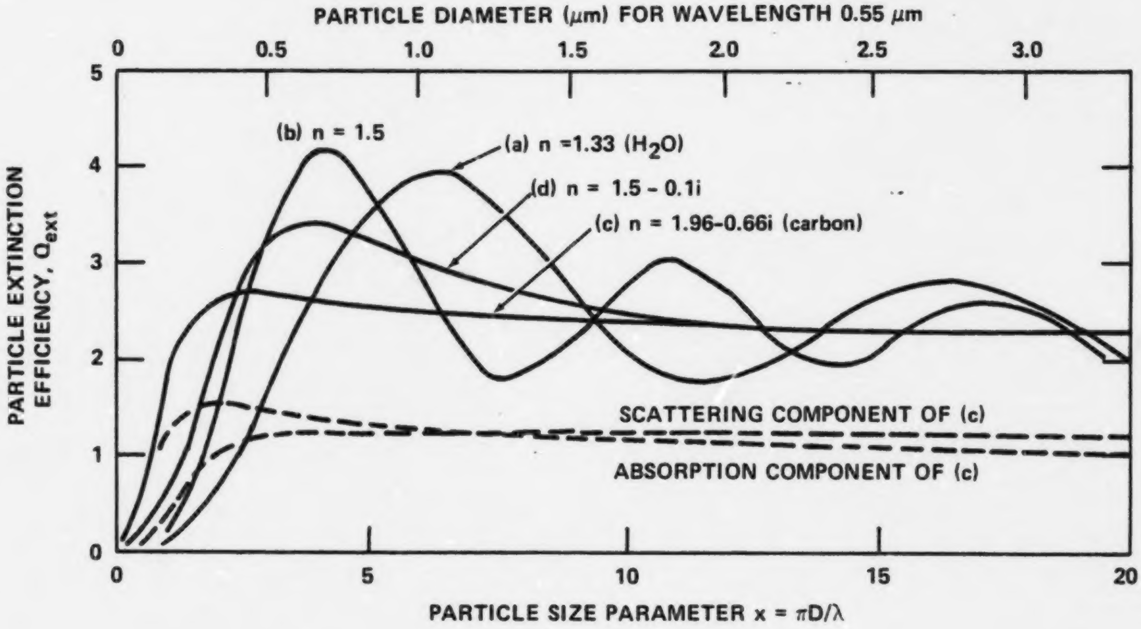


Figure 8. Extinction efficiency as a function of particle size parameter.

ESTIMATION PROCEDURE FOR CALCULATING PARTICLE COLLECTION EFFICIENCIES

The mathematical model for electrostatic precipitation allows for the use of estimation procedures for calculating particle collection efficiencies. Use of these procedures results in considerable savings in computer time since involved numerical techniques are not extensively employed. These procedures can be used to advantage when only gross trends in precipitator performance are required or when an estimating technique is desired in order to approximate the specific collection area required for a chosen overall mass collection efficiency so that a starting point for the more rigorous calculation can be easily obtained.

In the case where the operating applied voltage and current are known, particle charge, average electric field at the plate, and space charge effects are only estimated. Particle charge is calculated by using equation (15). The average electric field at the plate is calculated by dividing the applied voltage by the wire-to-plate spacing and scaling this value down by a factor of 1.75. This method of determining the average electric field at the plate is based on the examination of the results from model simulations of several full-scale precipitators which were collecting fly ash. Space charge effects are determined by reducing the free ion density and effective charge carrier mobility in the same procedure which leads to equation (16).

In the case where the operating applied voltage and current are not known, a voltage-current curve must be generated up to some specified operating applied voltage. The voltage-current calculation also determines the average electric field at the plate which is used in the estimation procedure. Particle charge is calculated by using equation (15). Space charge effects are determined by applying the procedure discussed earlier and in Appendix A.

It must be emphasized that these procedures are not expected to give results which will always be reasonable estimates. For any given set of conditions, these procedures may lead to predictions of precipitator performance which are in considerable error. However, in most cases, they should yield reasonable estimates of precipitator performance and their judicious use can lead to considerable savings in computer time.

SECTION 7

COMPUTER PROGRAMING OF THE MATHEMATICAL MODEL

DESCRIPTION OF THE COMPUTER PROGRAM

A computer program has been written in Fortran IV language in order to perform the mathematical operations associated with the model of electrostatic precipitation discussed in Section 6. Although the program has been developed using a Digital Equipment Corporation DEC 2020 computer, efforts have been made to make the program sufficiently generalized so that it can be easily implemented on other computers which have a Fortran compiler. Appendix B contains a list of the symbols used in the program along with their definitions and Appendix C contains a listing of the entire program. The program consists of a main program and 27 subroutines. The program contains 3,600 lines of code.

The following is a sequential list of the major operations which are performed by the computer program in order to determine fractional collection efficiencies and overall mass collection efficiency.

1. Data which are necessary to characterize precipitator performance are read into the main program.

2. If the inlet size distribution is known, it is read into the main program in the form of a histogram and it is "fit" to a log-normal distribution in subroutine LNFIT. Alternatively, parameters characteristic of a log-normal distribution can be read into the main program and a histogram is constructed in subroutine LNDIST in order to represent the inlet size distribution.

3. The number of particles in each size band of the inlet size distribution is calculated.

4. The precipitator is divided into specified incremental lengths.

5. If the operating applied voltage and current are not known, then subroutine EFLD2 is used to generate a clean-plate, clean-gas, voltage-current curve up to a specified value of operating applied voltage, to determine the free ion densities and charging fields for particle charging, and to calculate the electric field at the plate. If the operating applied voltage and current density are known, then subroutine SPCHG1 is used to calculate the amount of material removed per increment and the "particulate space charge" in each increment based on an estimated overall mass collection efficiency, to determine an effective charge carrier mobility, and to establish a reduced free ion density in each increment for use in determining particle charge.

6. If the operating applied voltage and current are known, then the average charging field is calculated using the applied voltage and the wire-to-plate spacing and the electric field at the plate is calculated in subroutine EFLD1.

7. The charge on each particle size at the end of each increment or subincrement of length is calculated in either CHARGN or by using equation (15), whichever is specified. In order to save computer time, the program contains a procedure which bypasses the charge calculation for a given particle size whenever the charge on that size does not change by more than 0.5% in two successive length increments in the same electrical section. Also, if the charge calculation for a given particle size has been bypassed in the last increment of a given electrical section and the applied voltage in this section is equal to or greater than that in the next section, then the charge calculation for this particle size will be bypassed in each increment in the next section.

8. If the operating applied voltage and current are unknown, then subroutine SPCHG2 is used to determine the "particulate space charge", the effective charge carrier mobility, and the operating current density.

9. A migration velocity for each particle size is calculated at the end of each length increment using equation (1).

10. The number of particles removed in each size band after each length increment of travel is calculated using equation (2).

11. After the required calculations have been performed in all length increments, an overall mass collection efficiency is calculated. If the operating applied voltage and current are known, then the calculated overall mass collection efficiency is compared with the input estimated efficiency. If the difference is greater than 0.05%, the program returns to the first length increment and repeats all calculations using the newly computed overall mass collection efficiency. Usually, only one iteration

is required. If the calculation of the overall mass collection efficiency has been based on a generated voltage-current curve, then no iteration over incremental lengths is performed.

12. After the overall mass collection efficiency has been obtained, an "effective" migration velocity is calculated for each size band and a precipitation rate parameter is computed based on the overall mass collection efficiency and equation (2).

The above operations complete the calculation of ideal performance that would be expected under a given set of input conditions and based on those physical mechanisms which are included in the model. In the following operations which are performed in subroutine ADJUST, corrections are made to the ideal projections by operating on the "effective" migration velocity for each particle size in order to account for unmodeled and nonideal effects.

13. For a given value of normalized gas velocity standard deviation, a correction factor is calculated for each "effective" migration velocity using the ideal efficiency for a given particle size and equation (17).

14. Using assumed values of number of stages and the percent loss per stage from reentrainment without rapping and/or gas sneakage, a correction factor is calculated for each "effective" migration velocity using the ideal efficiency for a given particle size and equation (19).

15. An "apparent" effective, no-rap migration velocity is obtained for each particle size by dividing the ideal values by the product of the two correction factors described above and a no-rap collection efficiency is calculated for each particle size using equation (2).

16. Using the correction factors given in Figure 7, the "apparent" effective, no-rap migration velocities are corrected in order to account for unmodeled effects and "adjusted" no-rap efficiencies are determined. An "adjusted" no-rap overall mass collection efficiency and precipitation rate parameter are calculated.

17. Losses in collection efficiency due to rapping reentrainment are obtained by reducing the mass collected in each size band under "adjusted" no-rap conditions according to either equation (24) or (25) and Figure 6. A collection efficiency and migration velocity with rapping are calculated for each particle size. An overall mass collection efficiency and precipitation rate parameter which account for losses due to rapping are calculated.

18. No-rap and no-rap + rap outlet size distributions are determined and outlet emissions are characterized by calculation

of $\Delta M/\Delta \log D$ for each size band for the "rapping puff" and no-rap and no-rap + rap conditions.

19. No-rap and no-rap + rap outlet size distributions are "fit" to a log-normal distribution.

20. The opacity of the outlet plume is calculated for the no-rap, rap, and no-rap + rap outlet distributions.

21. All input data and relevant parameters which have been calculated are printed.

If the dynamic rapping calculation is selected, subroutine RAPPE is used in place of subroutine ADJUST. In subroutine RAPPE, the corrections to the ideal performance projections are carried out in the same manner as in subroutine ADJUST except that no corrections are made for rapping reentrainment, i.e., only steps 13-16 are performed. At this point, the dust layer thickness up to the time of the rap is calculated, the dust is removed from those increments which are rapped and a portion of the removed dust is fit to a size distribution and stored for reintroduction into the gas stream. The operation of the program then returns to step 3 and continues from that point. This time, however, when the calculation reaches the n^{th} increment, the reentrained dust from the $(n-1)^{th}$ increment (assuming the $(n-1)^{th}$ increment was rapped) is added to the dust already present at that point so that the collection calculation will see a heavier dust load due to rapping reentrainment. The program repeats this calculation and recalculation process until the entire rapping scheme has been described mathematically. Pertinent ESP outlet information is printed after each cycle through the particle collection calculation.

In Figure 9, a simplified flow chart for the main program is given. This flow chart shows the major operations and logic branches and all subroutine callings. The input and output data for the computer program, along with the various uses of the program, will be discussed in detail in Volume 2 of this report. In the following subsection, the subroutines which are called by the main program will be discussed in detail.

DESCRIPTIONS OF THE SUBROUTINES

Subroutine SPCHG1

This subroutine determines the effect of "particulate space charge" in each increment of length by using the procedure leading to equation (16) in order to calculate an "effective" charge carrier mobility and average reduced ion density for particle charging. Figure 10 shows a detailed flow charge for this subroutine. All information which is transmitted between the main

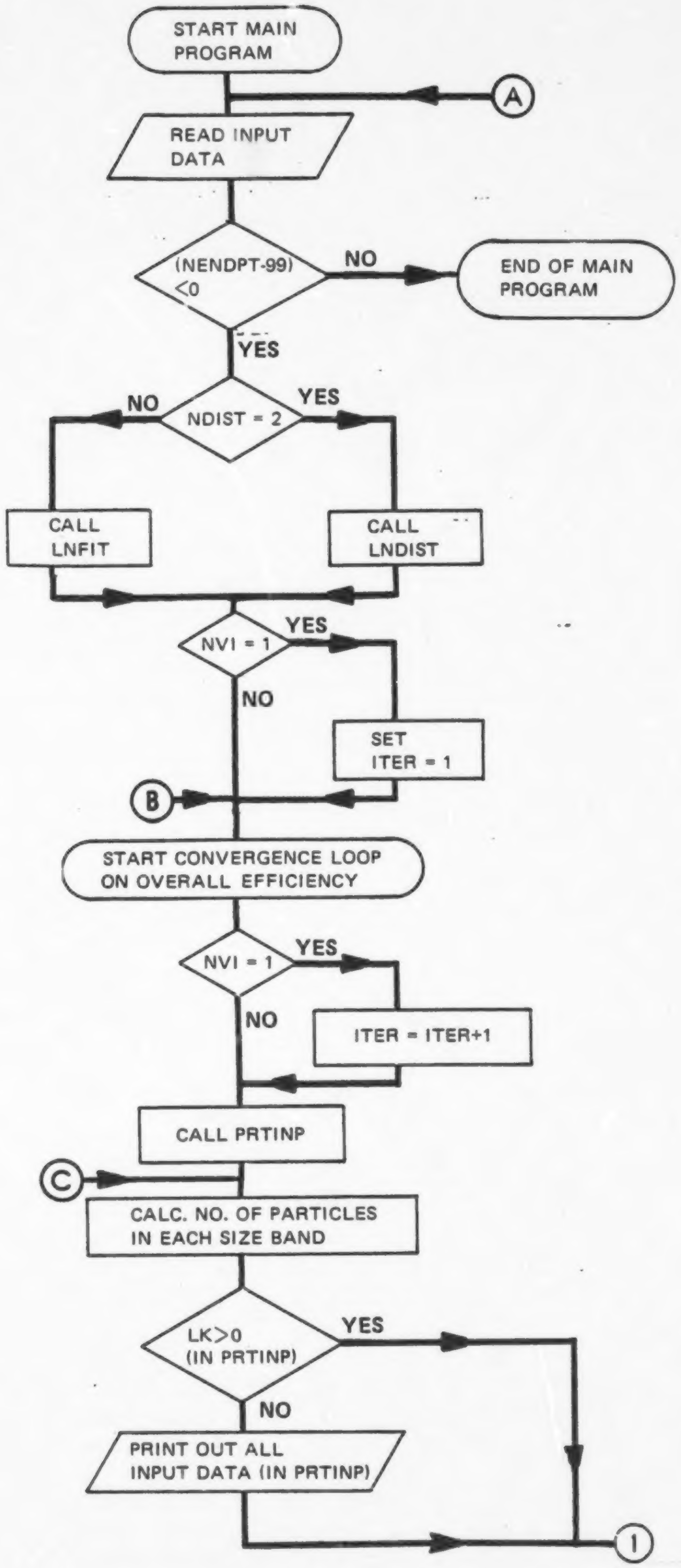

START MAIN PROGRAM
A
READ INPUT DATA
(NENDPT-99) <0
NO
END OF MAIN PROGRAM
YES
NO
NDIST = 2
YES
CALL LNFIT
CALL LNDIST
NVI = 1
YES
NO
SET ITER = 1
B
START CONVERGENCE LOOP ON OVERALL EFFICIENCY
NVI = 1
YES
NO
ITER = ITER+1
CALL PRTINP
C
CALC. NO. OF PARTICLES IN EACH SIZE BAND
LK>0 (IN PRTINP)
YES
NO
PRINT OUT ALL INPUT DATA (IN PRTINP)
1

Figure 9. Simplified flow chart for the entire program (Sheet 1 of 7).

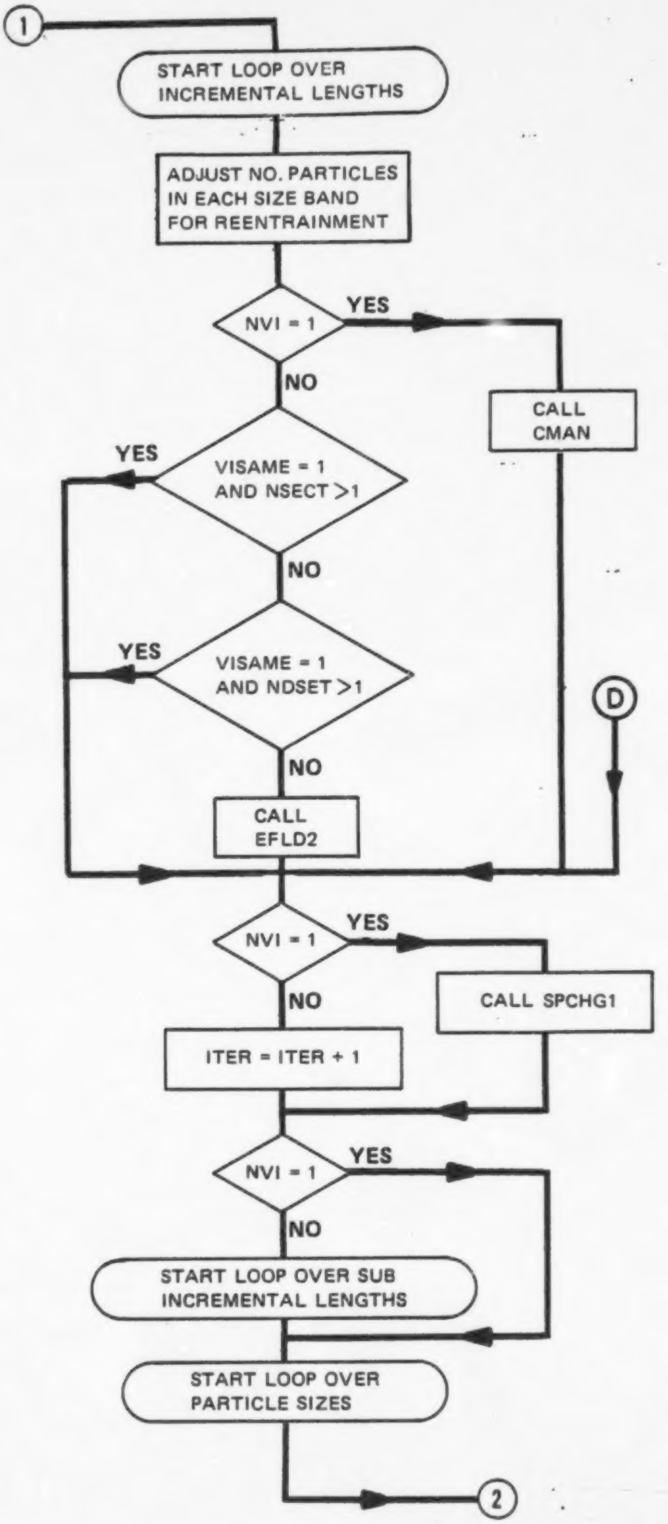

1
START LOOP OVER INCREMENTAL LENGTHS
ADJUST NO. PARTICLES IN EACH SIZE BAND FOR REENTRAINMENT
NVI = 1
YES
NO
CALL CMAN
VISAME = 1 AND NSECT >1
YES
NO
VISAME = 1 AND NDSET >1
YES
NO
D
CALL EFLD2
NVI = 1
YES
NO
CALL SPCHG1
ITER = ITER + 1
NVI = 1
YES
NO
START LOOP OVER SUB INCREMENTAL LENGTHS
START LOOP OVER PARTICLE SIZES
2

Figure 9. Simplified flow chart for the entire program (Sheet 2 of 7).

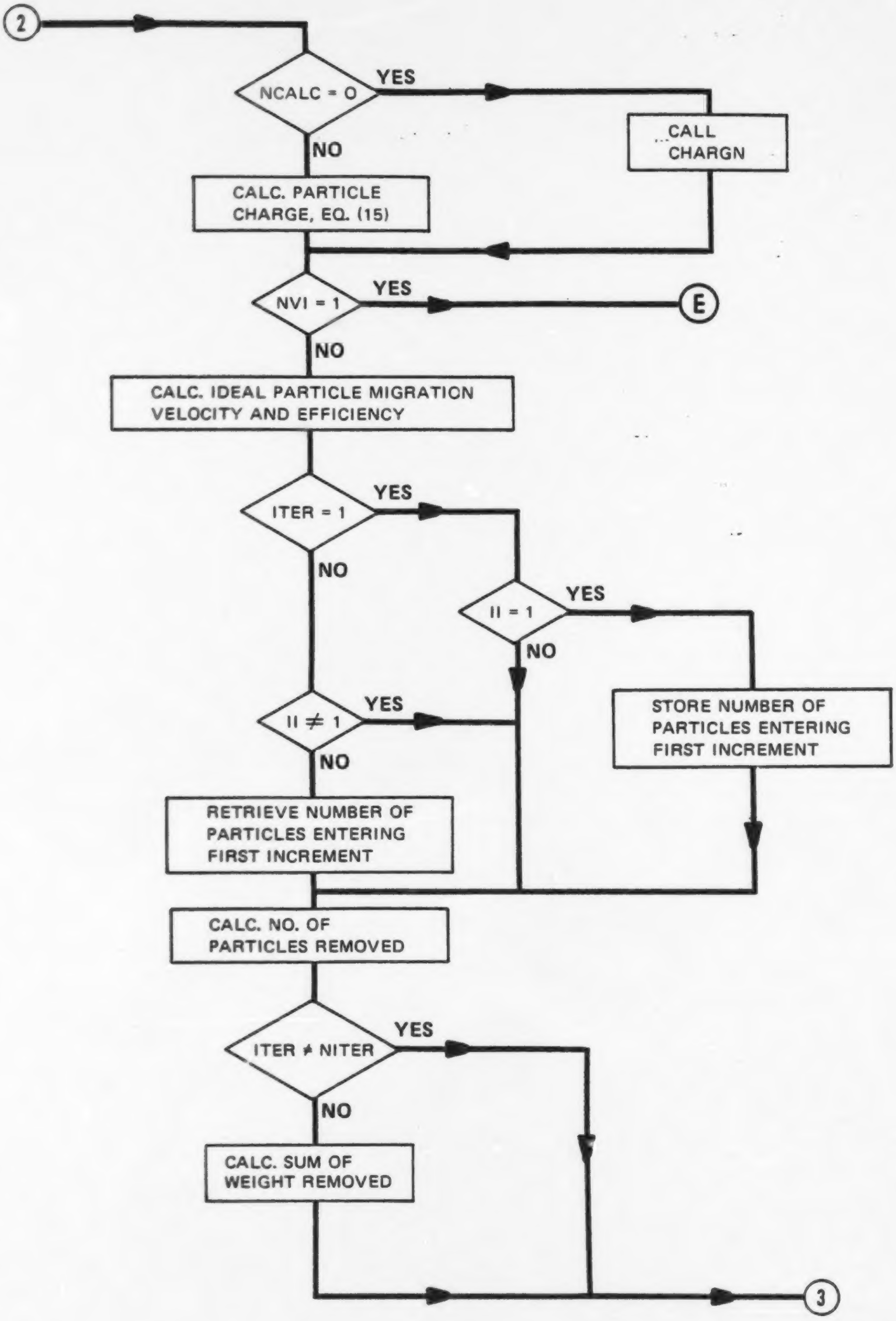
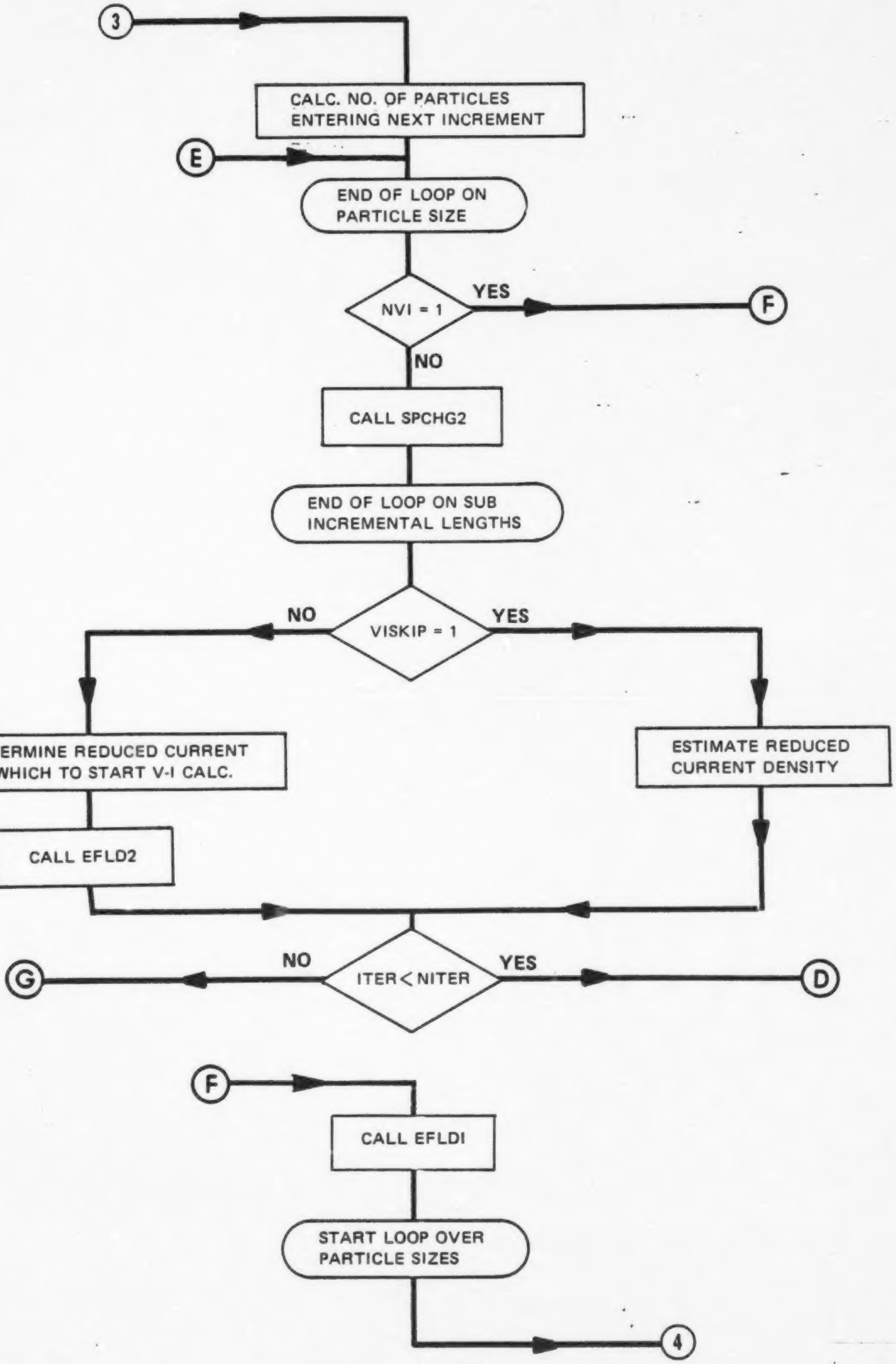

2
NCALC = O
YES
NO
CALL CHARGN
CALC. PARTICLE CHARGE, EQ. (15)
NVI = 1
YES
E
NO
CALC. IDEAL PARTICLE MIGRATION VELOCITY AND EFFICIENCY
ITER = 1
YES
NO
II = 1
YES
NO
II ≠ 1
YES
NO
STORE NUMBER OF PARTICLES ENTERING FIRST INCREMENT
RETRIEVE NUMBER OF PARTICLES ENTERING FIRST INCREMENT
CALC. NO. OF PARTICLES REMOVED
ITER ≠ NITER
YES
NO
CALC. SUM OF WEIGHT REMOVED
3

Figure 9. Simplified flow chart for the entire program (Sheet 3 of 7).



3
CALC. NO. OF PARTICLES ENTERING NEXT INCREMENT
E
END OF LOOP ON PARTICLE SIZE
NVI = 1
YES
F
NO
CALL SPCHG2
END OF LOOP ON SUB INCREMENTAL LENGTHS
NO
VISKIP = 1
YES
DETERMINE REDUCED CURRENT AT WHICH TO START V-I CALC.
ESTIMATE REDUCED CURRENT DENSITY
CALL EFLD2
G
NO
ITER < NITER
YES
D
F
CALL EFLDI
START LOOP OVER PARTICLE SIZES
4

Figure 9. Simplified flow chart for the entire program (Sheet 4 of 7).

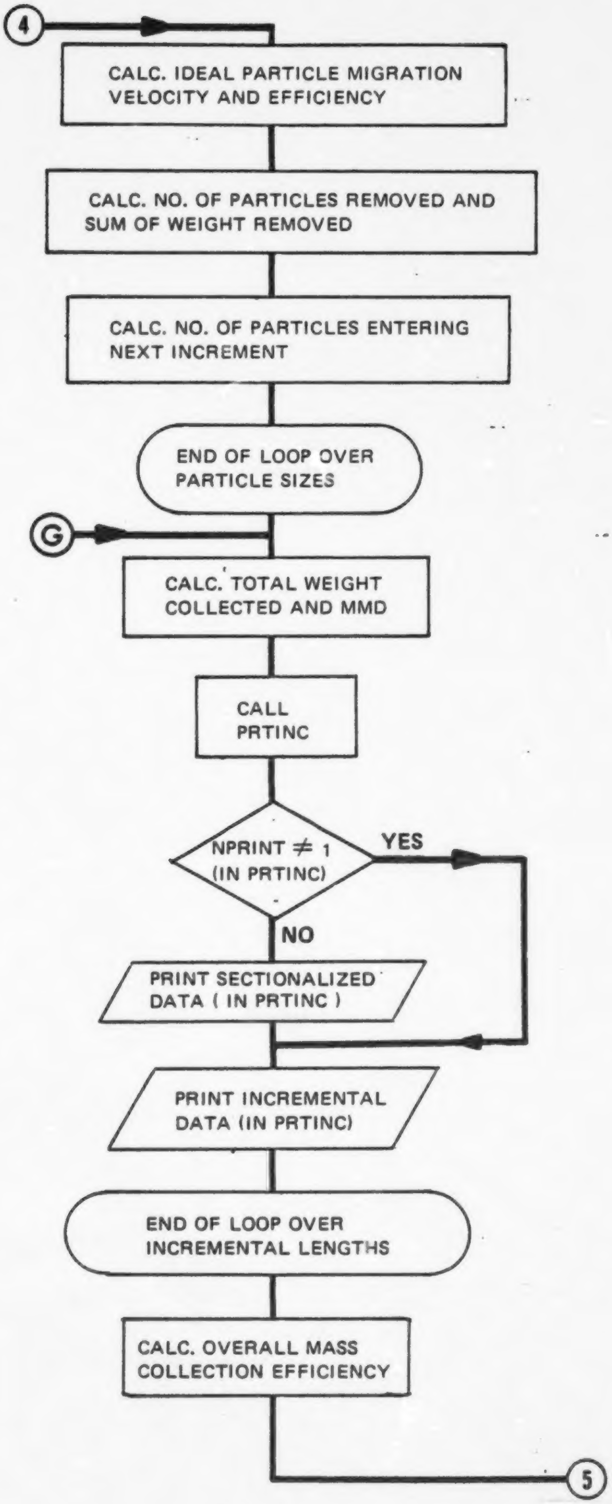

4
CALC. IDEAL PARTICLE MIGRATION VELOCITY AND EFFICIENCY
CALC. NO. OF PARTICLES REMOVED AND SUM OF WEIGHT REMOVED
CALC. NO. OF PARTICLES ENTERING NEXT INCREMENT
END OF LOOP OVER PARTICLE SIZES
G
CALC. TOTAL WEIGHT COLLECTED AND MMD
CALL PRTINC
NPRINT ≠ 1 (IN PRTINC)
YES
NO
PRINT SECTIONALIZED DATA (IN PRTINC)
PRINT INCREMENTAL DATA (IN PRTINC)
END OF LOOP OVER INCREMENTAL LENGTHS
CALC. OVERALL MASS COLLECTION EFFICIENCY
5

Figure 9. Simplified flow chart for the entire program (Sheet 5 of 7).

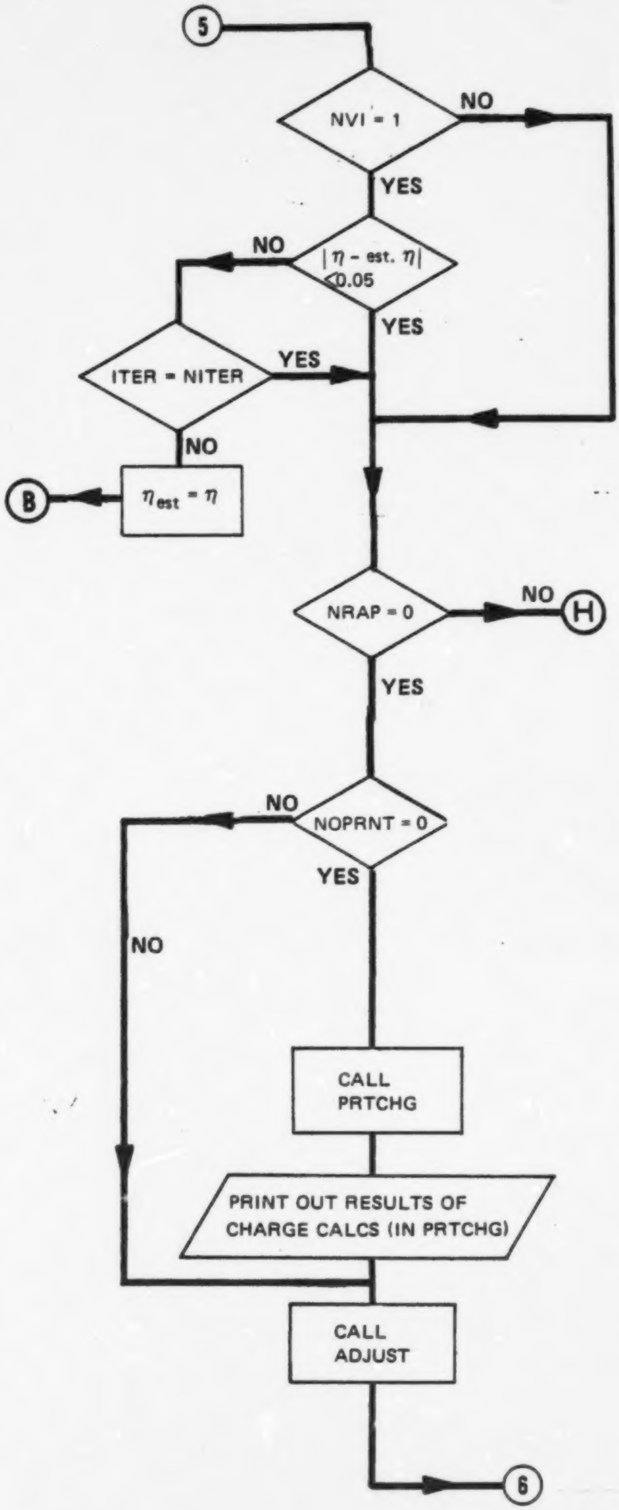

5
NVI = 1
NO
YES
NO
| η − est. η | <0.05
YES
ITER = NITER
YES
NO
B
η_est = η
NRAP = 0
NO
H
YES
NO
NOPRNT = 0
YES
NO
CALL PRTCHG
PRINT OUT RESULTS OF CHARGE CALCS (IN PRTCHG)
CALL ADJUST
6

Figure 9. Simplified flow chart for the entire program (Sheet 6 of 7).

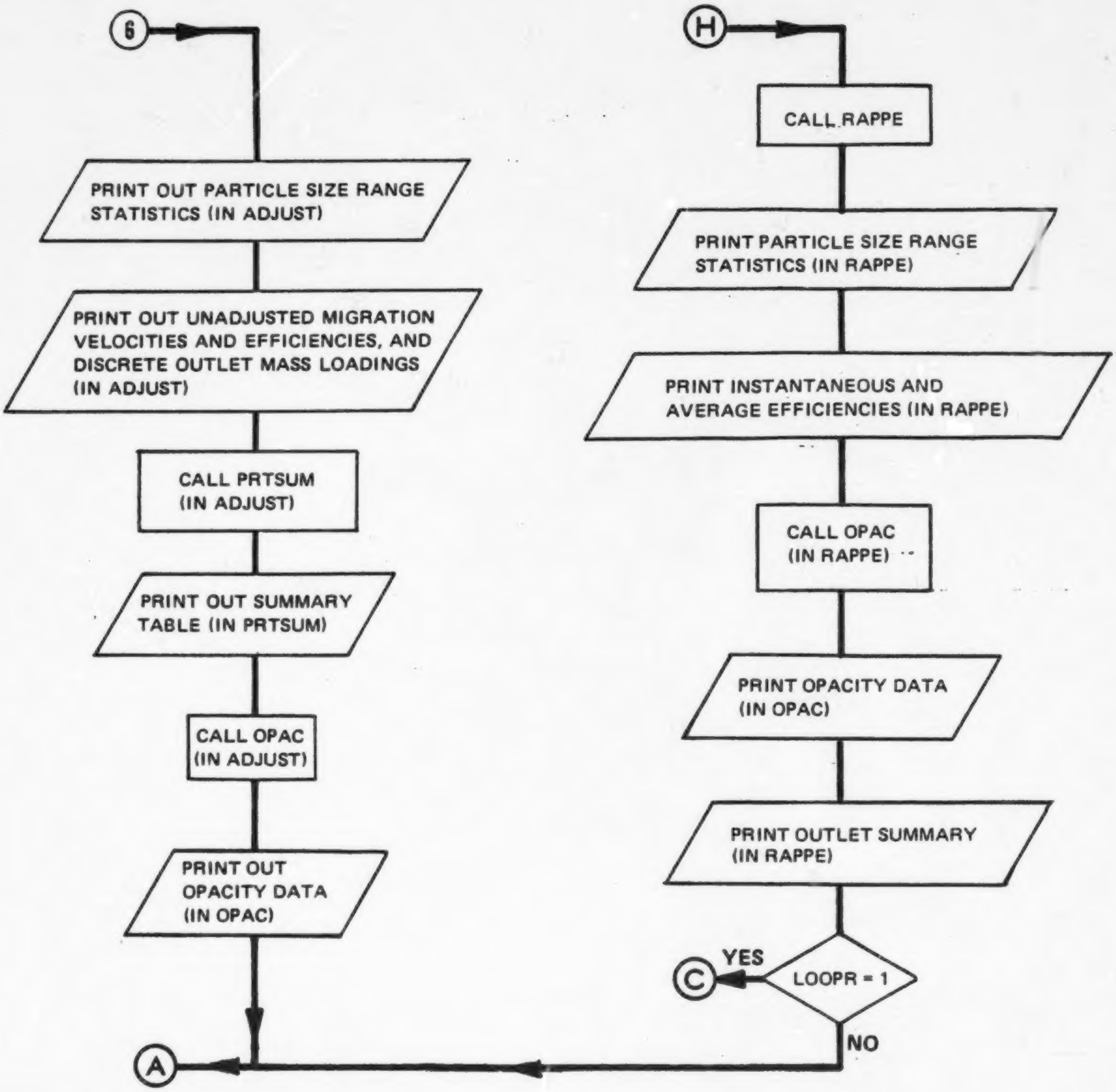

6
PRINT OUT PARTICLE SIZE RANGE STATISTICS (IN ADJUST)
PRINT OUT UNADJUSTED MIGRATION VELOCITIES AND EFFICIENCIES, AND DISCRETE OUTLET MASS LOADINGS (IN ADJUST)
CALL PRTSUM (IN ADJUST)
PRINT OUT SUMMARY TABLE (IN PRTSUM)
CALL OPAC (IN ADJUST)
PRINT OUT OPACITY DATA (IN OPAC)
A
H
CALL RAPPE
PRINT PARTICLE SIZE RANGE STATISTICS (IN RAPPE)
PRINT INSTANTANEOUS AND AVERAGE EFFICIENCIES (IN RAPPE)
CALL OPAC (IN RAPPE)
PRINT OPACITY DATA (IN OPAC)
PRINT OUTLET SUMMARY (IN RAPPE)
LOOPR = 1
YES
C
NO

Figure 9. Simplified flow chart for the entire program (Sheet 7 of 7).

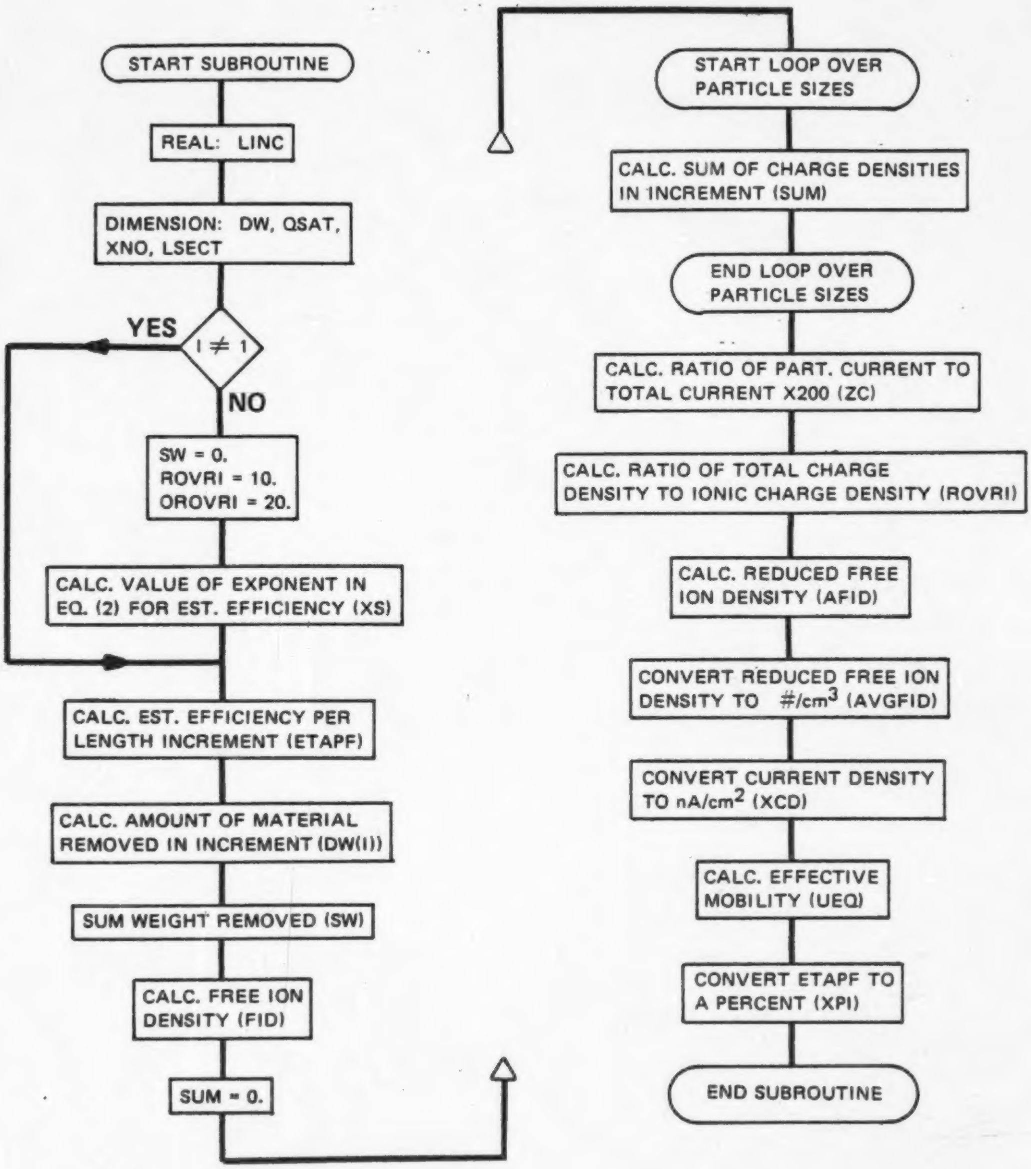

START SUBROUTINE
REAL: LINC
DIMENSION: DW, QSAT, XNO, LSECT
YES
I ≠ 1
NO
SW = 0.
ROVRI = 10.
OROVRI = 20.
CALC. VALUE OF EXPONENT IN EQ. (2) FOR EST. EFFICIENCY (XS)
CALC. EST. EFFICIENCY PER LENGTH INCREMENT (ETAPF)
CALC. AMOUNT OF MATERIAL REMOVED IN INCREMENT (DW(I))
SUM WEIGHT REMOVED (SW)
CALC. FREE ION DENSITY (FID)
SUM = 0.
START LOOP OVER PARTICLE SIZES
CALC. SUM OF CHARGE DENSITIES IN INCREMENT (SUM)
END LOOP OVER PARTICLE SIZES
CALC. RATIO OF PART. CURRENT TO TOTAL CURRENT X200 (ZC)
CALC. RATIO OF TOTAL CHARGE DENSITY TO IONIC CHARGE DENSITY (ROVRI)
CALC. REDUCED FREE ION DENSITY (AFID)
CONVERT REDUCED FREE ION DENSITY TO #/cm3 (AVGFID)
CONVERT CURRENT DENSITY TO nA/cm2 (XCD)
CALC. EFFECTIVE MOBILITY (UEQ)
CONVERT ETAPF TO A PERCENT (XPI)
END SUBROUTINE

Figure 10. Flow chart for subroutine SPCHG1.

program and this subroutine is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

SW - Estimated sum of material removed in successive increments of the ESP (kg/sec).

ROVRI - Ratio of total charge density to ionic charge density in a given increment of the ESP. Initialized to 10.0 to start procedure.

OROVRI - Ratio of total charge density to ionic charge density in previous increment of ESP. Initialized to 20.0 to start procedure.

XS - Computed value of exponential argument in equation (2) for the estimated overall efficiency.

ETAPF - Computed estimated overall collection fraction per given length increment.

DW(I) - Computed estimated amount of material removed in a given length increment (kg/sec).

QSAT(J) - Saturation charge on a given particle size (coul).

XNO(J) - Number of particles per unit volume of gas of a given particle size entering a given length increment (#/m^3).

W - Weight of material per unit time (mass flux) in a given length increment (kg/sec).

LSECT(K) - Number of length increments in a given electrical section.

TC - Total current in a given electrical section (A).

VG - Gas volume flow rate in a given electrical section (m^3/sec).

ETAO - Estimated overall mass efficiency of ESP (%).

FID - Computed free ion density in a given electrical section (#/m^3).

AFID - Computed reduced free ion density for particle charging in a given electrical section (#/m^3).

AVGFID - Reduced free ion density (#/cm^3).

XCD - Average current density at the plate in a given electrical section (nA/cm^2).

U - Ion mobility in a given electrical section (m^2/V-sec).

UEQ - Effective charge carrier mobility in a given length increment (m^2/V-sec). Restricted to a lower limit of 1 x 10^{-4} m^2/V-sec in main program to avoid convergence difficulties when used in subroutine EFLD1.

I - Index specifying the given length increment. Can not exceed a value of 50.

NSECT - Indicator specifying the given electrical section of the ESP. Can not exceed a value of 10.

LINC - Length of each increment in a given electrical section (m).

PL - Total electrical length of ESP (m).

CD - Average current density at the plate in a given electrical section (A/m^2).

E - Electronic charge (coul).

ERAVG - Average electric field between the wire and plate (V/m).

NS - Number of particle size bands in size distribution histogram. Can not exceed a value of 20.

XPI - Computed estimated overall collection efficiency per given length increment (%).

Of the above variables, the values of the following must be provided by the main program: QSAT(J), XNO(J), W, LSECT(K), TC, VG, ETAO, U, I, NSECT, LINC, PL, CD, E, ERAVG, and NS. The values of the following variables are determined in the subroutine: SW, ROVRI, OROVRI, XS, ETAPF, DW, FID, AFID, AVGFID, XCD, UEQ, and XPI. In the above arrays, I, J, and K can not exceed 45, 20, and 10, respectively. The restrictions on I, J, and K limit the number of length increments, the number of particle size bands, and the number of electrical sections, respectively.

Subroutine SPCHG2

This subroutine approximates the effect of particulate space charge in each subincrement of length by using the procedure discussed earlier in this report and in Appendix A to calculate an effective charge carrier mobility. Figure 11 shows a detailed flow chart for this subroutine. Information which is transmitted

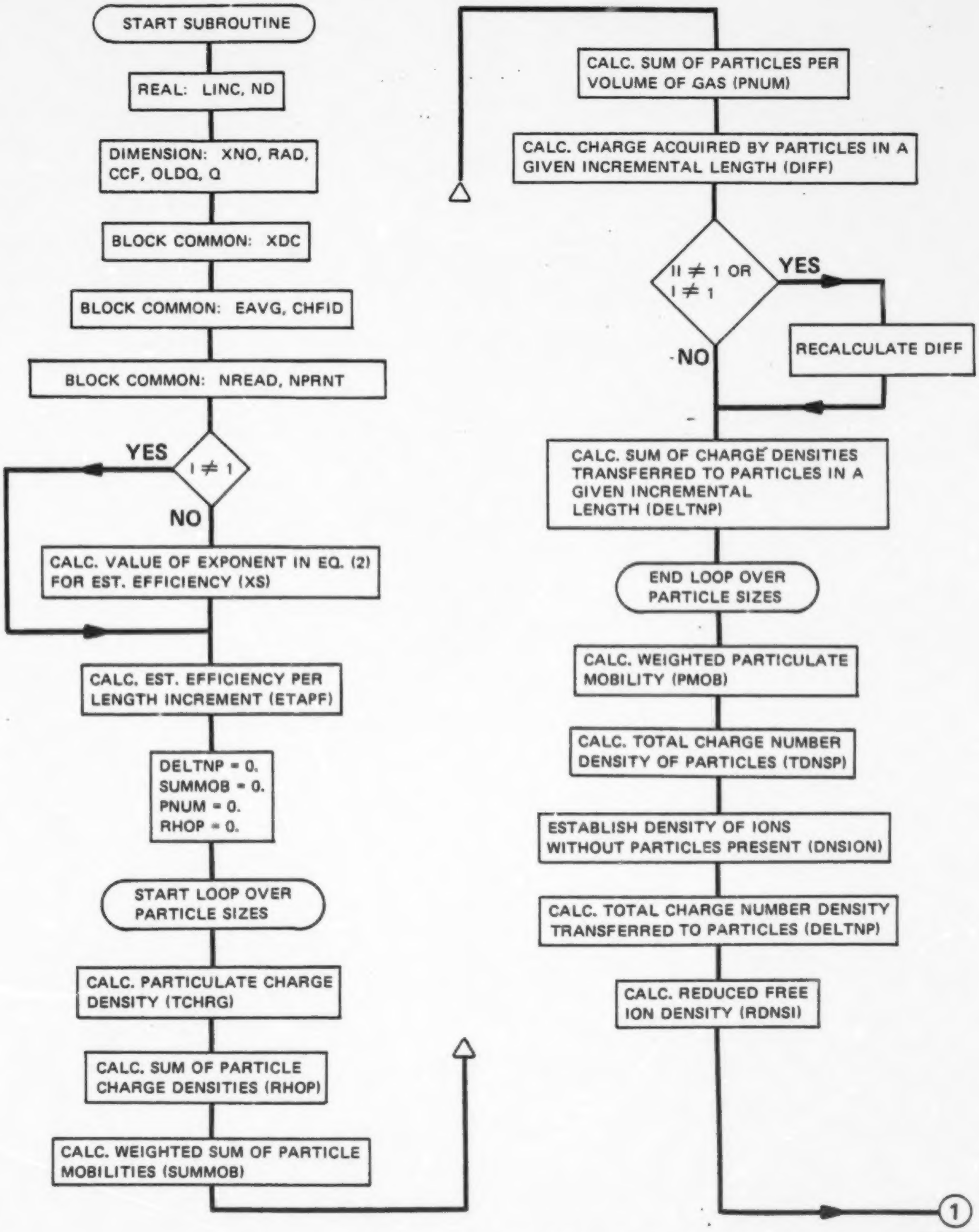

START SUBROUTINE
REAL: LINC, ND
DIMENSION: XNO, RAD, CCF, OLDQ, Q
BLOCK COMMON: XDC
BLOCK COMMON: EAVG, CHFID
BLOCK COMMON: NREAD, NPRNT
YES
I ≠ 1
NO
CALC. VALUE OF EXPONENT IN EQ. (2) FOR EST. EFFICIENCY (XS)
CALC. EST. EFFICIENCY PER LENGTH INCREMENT (ETAPF)
DELTNP = 0.
SUMMOB = 0.
PNUM = 0.
RHOP = 0.
START LOOP OVER PARTICLE SIZES
CALC. PARTICULATE CHARGE DENSITY (TCHRG)
CALC. SUM OF PARTICLE CHARGE DENSITIES (RHOP)
CALC. WEIGHTED SUM OF PARTICLE MOBILITIES (SUMMOB)
CALC. SUM OF PARTICLES PER VOLUME OF GAS (PNUM)
CALC. CHARGE ACQUIRED BY PARTICLES IN A GIVEN INCREMENTAL LENGTH (DIFF)
II ≠ 1 OR I ≠ 1
YES
NO
RECALCULATE DIFF
CALC. SUM OF CHARGE DENSITIES TRANSFERRED TO PARTICLES IN A GIVEN INCREMENTAL LENGTH (DELTNP)
END LOOP OVER PARTICLE SIZES
CALC. WEIGHTED PARTICULATE MOBILITY (PMOB)
CALC. TOTAL CHARGE NUMBER DENSITY OF PARTICLES (TDNSP)
ESTABLISH DENSITY OF IONS WITHOUT PARTICLES PRESENT (DNSION)
CALC. TOTAL CHARGE NUMBER DENSITY TRANSFERRED TO PARTICLES (DELTNP)
CALC. REDUCED FREE ION DENSITY (RDNSI)
①

Figure 11. Flow chart for subroutine SPCHG2 (Sheet 1 of 2).

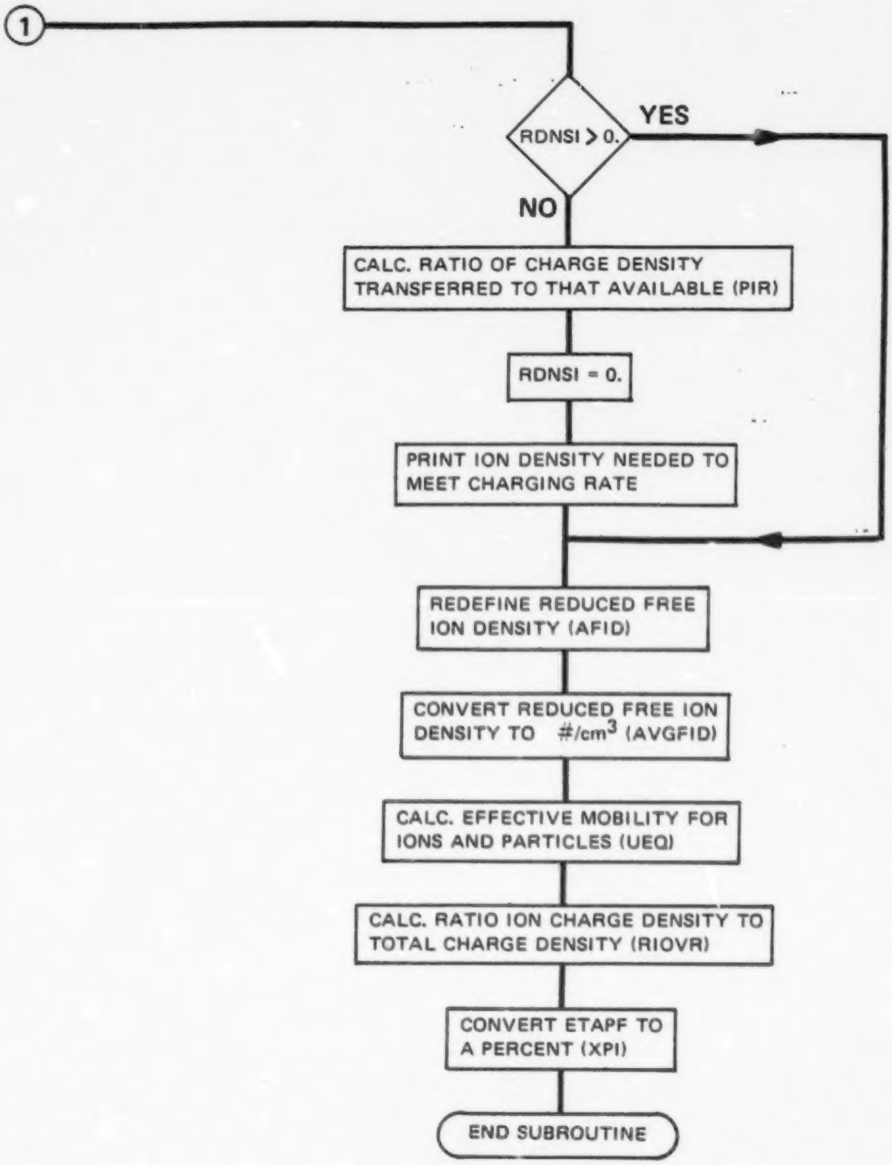

①
RDNSI > 0.
YES
NO
CALC. RATIO OF CHARGE DENSITY TRANSFERRED TO THAT AVAILABLE (PIR)
RDNSI = 0.
PRINT ION DENSITY NEEDED TO MEET CHARGING RATE
REDEFINE REDUCED FREE ION DENSITY (AFID)
CONVERT REDUCED FREE ION DENSITY TO #/cm3 (AVGFID)
CALC. EFFECTIVE MOBILITY FOR IONS AND PARTICLES (UEQ)
CALC. RATIO ION CHARGE DENSITY TO TOTAL CHARGE DENSITY (RIOVR)
CONVERT ETAPF TO A PERCENT (XPI)
END SUBROUTINE

Figure 11. Flow chart for subroutine SPCHG2 (Sheet 2 of 2).

between the main program and this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

NS - Number of particle size bands in size distribution histogram. Can not exceed a value of 20.

XNO(J) - Number of particles per unit volume of gas of a given particle size entering a given length increment (#/m^3).

VIS - Gas viscosity in a given electrical section (kg/m-sec).

RAD(J) - Radius of a given particle size (m).

LINC - Length of each increment in a given electrical section (m).

E - Electronic charge (coul).

U - Ion mobility in a given electrical section (m^2/V-sec).

ERAVG - Average electric field between the wire and plate (V/m).

DNSION - Ion density in the absence of particles (#/m^3).

DELTNP - Number density of charges transferred from ions to particles in a given subincrement of length (#/m^3).

SUMMOB - Weighted summation of particle mobilities (m^2/V-sec/m^3).

PNUM - Total number of particles per unit volume of gas entering a given subincrement of length (#/m^3).

RHOP - Total average particulate charge density in a given subincrement of length (coul/m^3).

TCHRG - Average particle charge density for a given particle size in a given subincrement of length (coul/m^3).

PMOB - Weighted particulate mobility in a given subincrement of length (m^2/V-sec).

TDNSP - Total average particulate charge number density in a given subincrement of length (#/m^3).

RDNSI, AFID - Average reduced ion density in a given subincrement of length (#/m^3).

UEQ - Effective charge carrier mobility in a given subincrement of length (m^2/V-sec).

AVGFID - Average reduced ion density in a given subincrement of length (#/cm^3).

RIOVR - Ratio of ionic charge density to total charge density in a given subincrement of length.

I - Index specifying the given length increment. Can not exceed a value of 45.

XS - Computed value of exponential argument in equation (2) for the design overall efficiency.

ETAO - Design overall mass efficiency of ESP (%).

PL - Total electrical length of ESP (m).

ETAPF - Computed design overall collection fraction per given length increment.

CCF(J) - Cunningham slip correction factor for a given particle size.

XPI - Computed design overall collection efficiency per given length increment (%).

OLDQ(J) - Value of charge for a given particle size acquired through all subincrements of length up to the subincrement under consideration (coul).

Q(J) - Value of charge for a given particle size acquired through the subincrement of length under consideration (coul).

II - Index specifying the given subincrement of length. Can not exceed a value of 30.

NSECT - Indicator specifying the given electrical section of the ESP. Can not exceed a value of 10.

The following is a list of the necessary variables which are in common with the main program.

XDC(I,J) - Charge on a given particle size at the end of a given length increment (coul).

EAVG(K) - Average electric field in a given subincrement of length (V/m).

CHRID(K) - Average ion density in the absence of particles in a given subincrement of length (#/m^3).

NPRNT - Indicator which specifies the logical unit number of the printer.

Of the above variables, the values of the following must be provided by the main program: NS, XNO, VIS, RAD, LINC, E, U, ERAVG, I, ETAO, PL, CCF, OLDQ, Q, II, ND, NSECT, XDC, EAVG, CHFID, and NPRNT. The values of the following variables are determined in the subroutine: DNSION, DELTNP, SUMMOB, PNUM, RHOP, TCHRG, PMOB, TDNSP, RDNSI, AFID, UEQ, AVGFID, RIOVR, XS, ETAPF, and XPI. In the above arrays, I, J, and K can not exceed values of 45, 20, and 30, respectively. The restrictions on I, J, and K limit the number of length increments, the number of particle size bands, and the number of subincremental lengths in a given length increment, respectively. If, in a given subincrement of length, there are not enough free ions available to meet the charging rates of all the particle sizes, then the subroutine prints out a message which states the increase in ion density necessary to meet the charging rates. In this case, the free ion density is defined as zero and it is assumed that the charging rate was met.

Subroutine CMAN

This subroutine calculates an initial estimate of the electric potential at each point in a grid which is established in either EFLD1 or EFLD2 for the purpose of determining the electrical conditions in a wire-plate precipitator. The calculation is based on an electrostatic solution for a wire-plate geometry. Thus, this initial estimate does not include the effects of space charge. The equation which is used to calculate the initial values of electric potential at the grid points is given by[32]

$$V(x,y) = V_w \frac{\sum_{m=-\infty}^{\infty} \ln \left[\frac{\cosh \pi(y-2mS_y)/2S_x - \cos(\pi x/2S_x)}{\cosh \pi(y-2mS_y)/2S_x + \cos(\pi x/2S_x)}\right]}{\sum_{m=-\infty}^{\infty} \ln \left[\frac{\cosh(\pi m S_y/S_x) - \cos(\pi r_w/2S_x)}{\cosh(\pi m S_y/S_x) + \cos(\pi r_w/2S_x)}\right]}, \qquad (27)$$

where $V(x,y)$ = electrical potential (V),

V_w = applied voltage (V),

S_x = wire-to-plate spacing (m),

S_y = one half wire-to-wire spacing (m),

r_w = radius of corona wire (m),

x = coordinate position measured toward plate with the corona wire as origin (m), and y = coordinate position measured parallel to plates with the corona wire as origin (m).

In practice the series converges rapidly and only a few terms need be evaluated. The sums in equation (27) are performed over the number of wires in a given gas passage of a given electrical section.

Figure 12 shows a detailed flow chart for this subroutine. Information which is transmitted between the main program, other subroutines, and this subroutine is transferred through calling arguments and a block common statement. The following is a sequential list of the calling arguments and their descriptions.

VW - Electric potential at the wire (V).

NX - Number of grid points in the x-direction. Can not exceed a value of 15.

NY - Number of grid points in the y-direction. Can not exceed a value of 15.

SX - Wire-to-plate spacing (m).

SY - One-half wire-to-wire spacing (m).

PI - Value of the constant pi.

AC - Radius of discharge electrode (m).

NWIRE - Number of wires per gas passage per electrical section.

The following variable is in common with the main program and subroutine EFLD2.

VCOOP(I,J) - Initial estimate of potential at points in the grid (V). I and J can not exceed a value of 15.

Of the above variables, the values of the following must be provided by the main program: VW, NX, NY, SX, SY, PI, AC, and NWIRE. VCOOP is determined in the subroutine. The restrictions on I and J limit the number of grid points in the x-direction and the number of grid points in the y-direction, respectively.

Subroutine EFLD1

This subroutine calculates the average electric field at the plate of a wire-plate precipitator. Its usage depends upon measured or known values of applied voltage and current. The electric

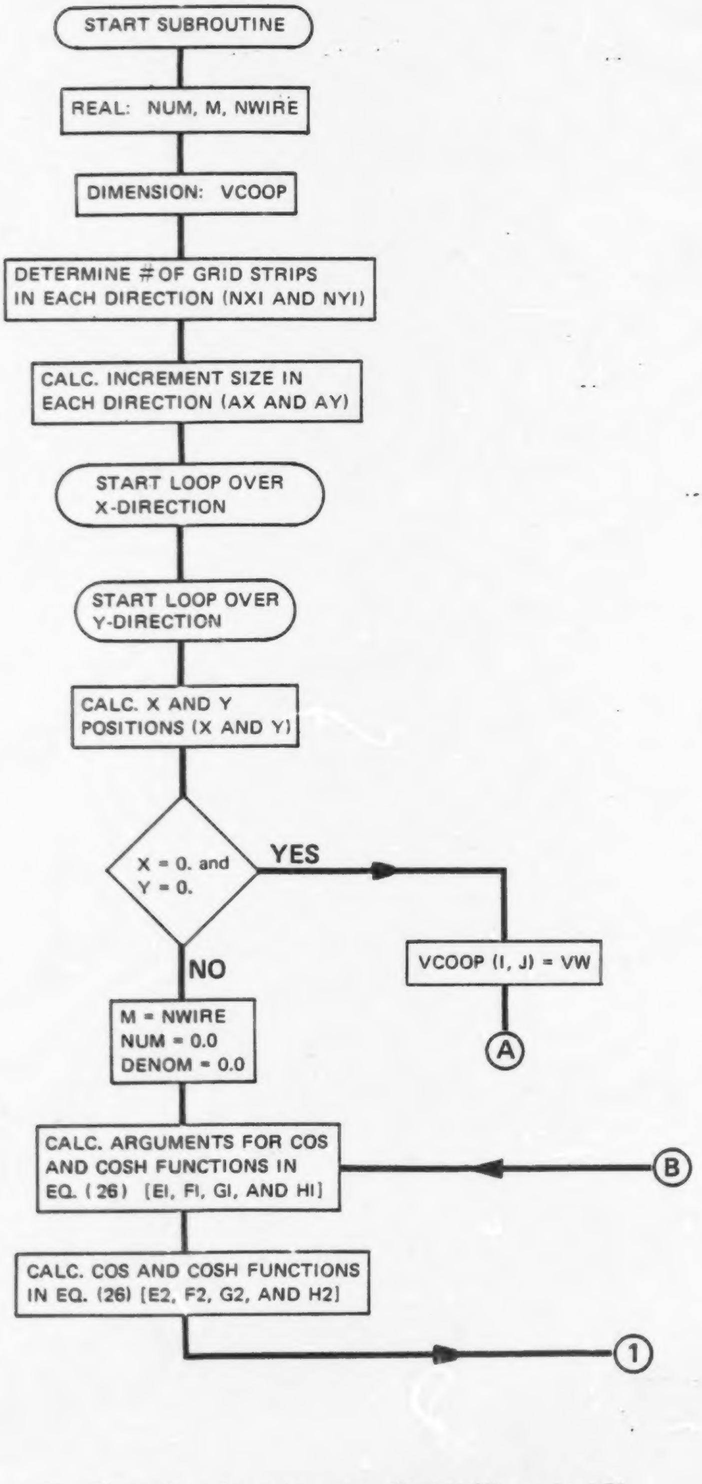

START SUBROUTINE
REAL: NUM, M, NWIRE
DIMENSION: VCOOP
DETERMINE # OF GRID STRIPS IN EACH DIRECTION (NXI AND NYI)
CALC. INCREMENT SIZE IN EACH DIRECTION (AX AND AY)
START LOOP OVER X-DIRECTION
START LOOP OVER Y-DIRECTION
CALC. X AND Y POSITIONS (X AND Y)
X = 0. and Y = 0.
YES
VCOOP (I, J) = VW
A
NO
M = NWIRE
NUM = 0.0
DENOM = 0.0
CALC. ARGUMENTS FOR COS AND COSH FUNCTIONS IN EQ. (26) [EI, FI, GI, AND HI]
B
CALC. COS AND COSH FUNCTIONS IN EQ. (26) [E2, F2, G2, AND H2]
1

Figure 12. Flow chart for subroutine CMAN (Sheet 1 of 2).

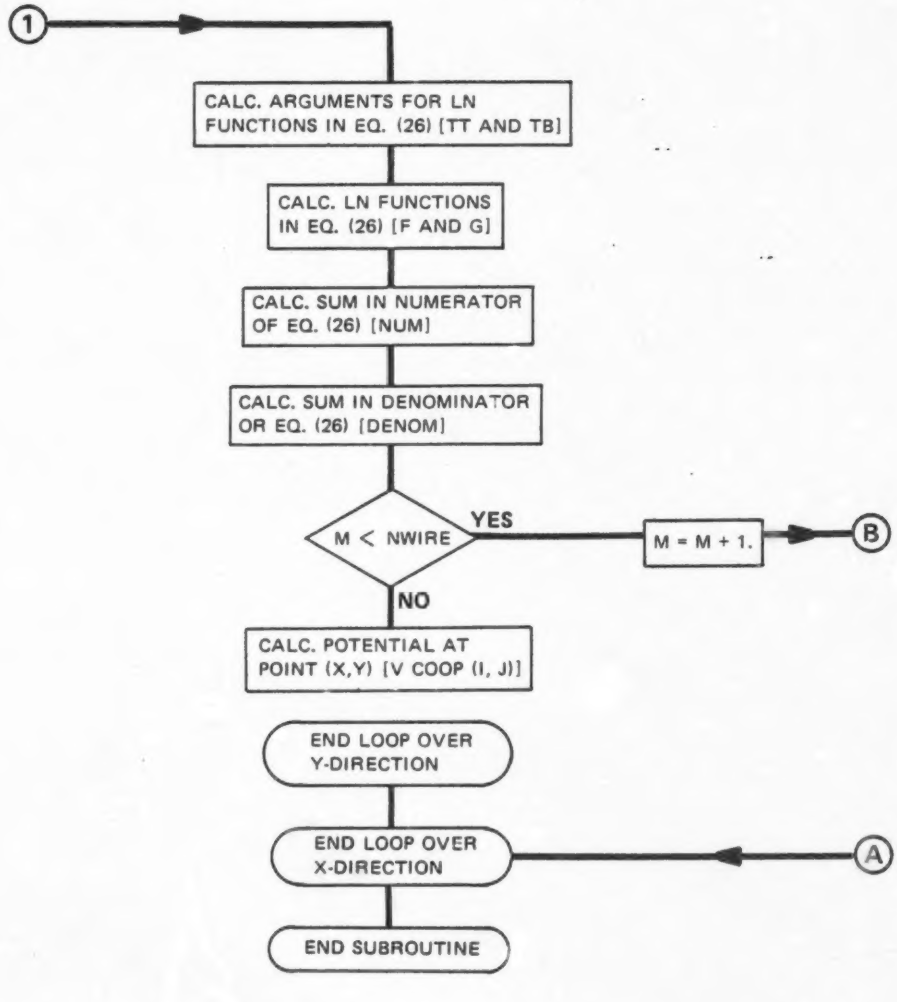

1
CALC. ARGUMENTS FOR LN FUNCTIONS IN EQ. (26) [TT AND TB]
CALC. LN FUNCTIONS IN EQ. (26) [F AND G]
CALC. SUM IN NUMERATOR OF EQ. (26) [NUM]
CALC. SUM IN DENOMINATOR OR EQ. (26) [DENOM]
M < NWIRE
YES
M = M + 1.
B
NO
CALC. POTENTIAL AT POINT (X,Y) [V COOP (I, J)]
END LOOP OVER Y-DIRECTION
END LOOP OVER X-DIRECTION
A
END SUBROUTINE

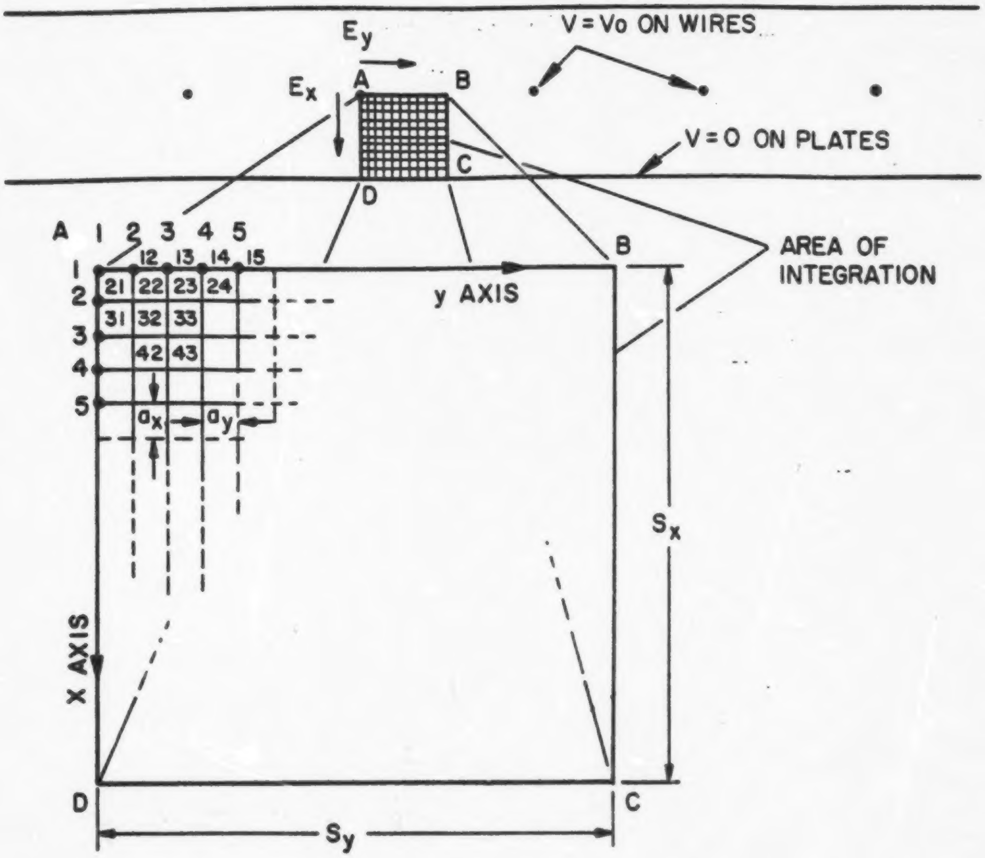
Figure 12. Flow chart for subroutine CMAN (Sheet 2 of 2).

field at the plate is found by solving equations (9) and (10) simultaneously subject to the existing boundary conditions. The method for doing this has been changed to greatly decrease the time required for the calculation. The new procedure incorporates the dominant eigenvalue method of convergence acceleration adapted to the ESP model by R. M. Felder and E. Arce-Medina.[5] In this procedure the solutions to equations (9) and (10) are initially sought by the same iterative technique used in previous versions of the model. However, if the derived values of the potential have not converged in a preset number of iterations, a potential adjustment factor is derived based on the changes in the potential due to the previous two iterations. This adjustment factor has a much greater effect on the potential than does the iterative process. After the potential is adjusted, the program resumes the iterative process in order to check for potential convergence and to build an iterative history in preparation for the next potential adjustment. The result of this process is a 90% reduction in the number of iterations required for the potential solution to converge.

In solving the field equations, the corona zone surrounding the discharge wire is considered only as a source of ions and the high values of electric field intensity existing in this region are not treated in the calculation. The region outside the corona zone, where the values of electric field intensity are relatively low, is referred to as the space-charge zone and is assumed to contain unipolar ions.

Figure 13 shows the basic area of interest in the precipitator for which equations (9) and (10) are solved. Figure 13 also includes the geometry and nomenclature used in the numerical analysis. Due to the symmetry of the problem it is necessary to integrate only over the rectangle shown in Figure 13 and then assert that the solutions hold for all similar rectangles within the duct. In this manner the entire two-dimensional area can be taken into account. In the actual numerical procedure, occasions occur when values of V, E, and ρ from positions outside the rectangle are used. In this case it is justified to assign to the functions V, E, and ρ the same values they had at symmetrically located points within the area of the rectangle. This is necessary in order for the integration to include values of V and ρ which exist on the boundaries in such a way that they converge toward an exact solution along with the interior points.

In order to employ the numerical technique, the area of interest is divided into a fine rectangular grid as shown in Figure 14. Point "0" is the point of interest for the following discussion. However, once V_0, E_0, and ρ_0 are calculated here, the label "0" is moved to a neighboring point and the calculation



Ey
V = Vo ON WIRES
Ex
A
B
C
D
V = 0 ON PLATES
AREA OF INTEGRATION
A 1 2 3 4 5
1 2 3 4 5
12 13 14 15
21 22 23 24
31 32 33
42 43
ax
ay
y AXIS
X AXIS
B
C
D
Sx
Sy

S_y = ONE HALF WIRE TO WIRE SPACING
S_x = WIRE TO PLATE SPACING
a_x a_y = INCREMENT SIZES FOR INTEGRATION
V_0 = APPLIED VOLTAGE
E_x = COMPONENT OF ELECTRIC FIELD PERPENDICULAR TO PLATE
E_y = LONGITUDINAL COMPONENT OF ELECTRIC FIELD
j = AVERAGE CURRENT DENSITY

Figure 13. Nomenclature used in the numerical analysis of the electrical conditions in wire-plate precipitators.

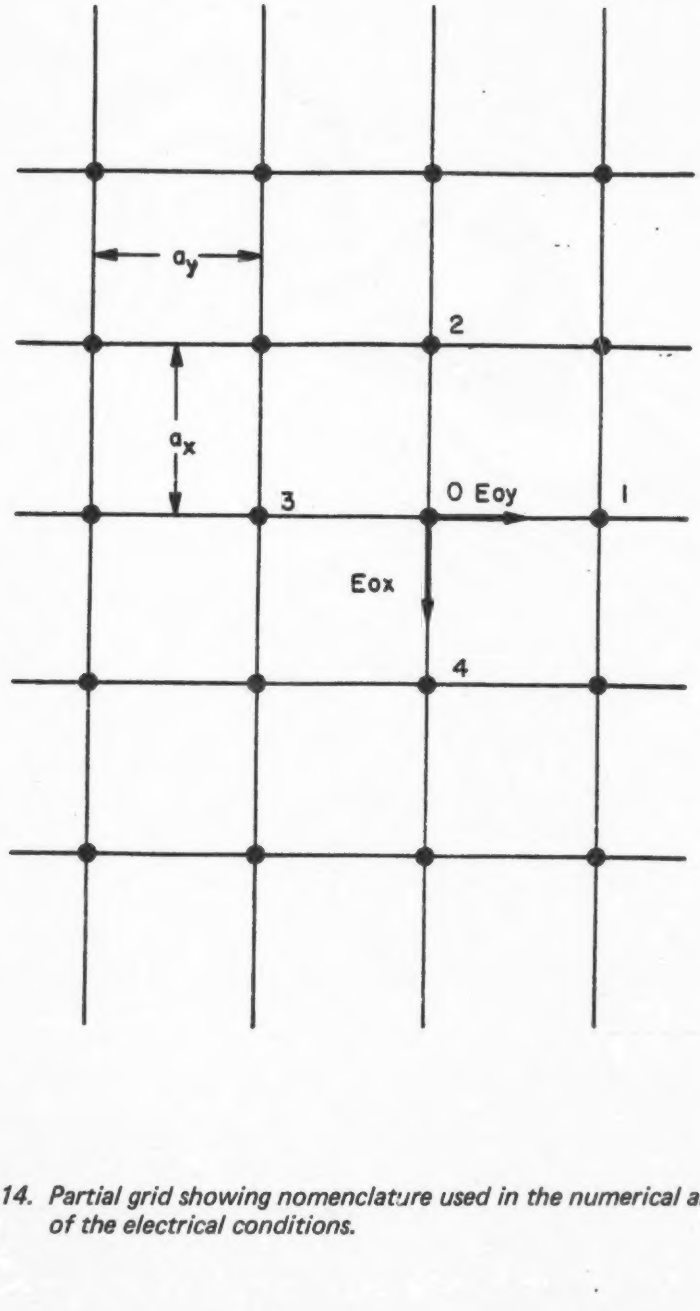

a_y
a_x
2
3
0 Eoy
1
Eox
4

Figure 14. Partial grid showing nomenclature used in the numerical analysis of the electrical conditions.

repeated. Each point in the grid would eventually become point "0".

From Figure 14,

$$\frac{\Delta V_0}{\Delta x} = \frac{1}{2a_x}(V_4 - V_2),$$

$$\frac{\Delta V_0}{\Delta y} = \frac{1}{2a_y}(V_1 - V_3),$$

$$\frac{\Delta^2 V_0}{\Delta x^2} = \frac{V_4 + V_2 - 2V_0}{a_x^2}, \qquad (28)$$

and

$$\frac{\Delta^2 V_0}{\Delta y^2} = \frac{V_3 + V_1 - 2V_0}{a_y^2} \qquad (29)$$

Equations (28) and (29) can be used in equation (9) and the resulting equation can be solved for V_0 to give

$$V_0 \simeq \frac{1}{2(a_x^2 + a_y^2)} \left[a_y^2 (V_2 + V_4) + a_x^2 (V_1 + V_3) + \frac{a_x^2 a_y^2 \rho_0}{\varepsilon_0}\right]. \qquad (30)$$

Again, from Figure 14,

$$\frac{\Delta \rho_0}{\Delta x} = \frac{\rho_0 - \rho_2}{a_x}, \qquad (31)$$

$$\frac{\Delta \rho_0}{\Delta y} = \frac{\rho_0 - \rho_3}{a_y}, \qquad (32)$$

$$\frac{\Delta b_0}{\Delta x} = \frac{b_0 - b_2}{a_x}, \qquad (33)$$

and

$$\frac{\Delta b_0}{\Delta y} = \frac{b_0 - b_3}{a_y}. \qquad (34)$$

Equations (31)-(34) can be used in equation (10) and the resulting equation can be solved for ρ_0 to give

$$\rho_0 = -\alpha \pm \sqrt{\alpha^2 + \beta}, \qquad (35)$$

where

$$\alpha = \frac{\varepsilon_0(2a_y b_0 E_{0x} + 2a_x b_0 E_{0y} - a_y b_2 E_{0x} - a_x b_3 E_{0y})}{2a_x a_y b_0} ,$$

and

$$\beta = \frac{\varepsilon_0(a_y E_{0x}\rho_2 + a_x E_{0y}\rho_3)}{a_x a_y} .$$

In subroutine EFLD1, solutions to equations (30) and (35) are obtained subject to the following boundary conditions:

(a) $V = V_w$ (applied voltage) at the wire;

(b) J_p = known or measured average current density at the plate;

(c) $V = 0$ on the plate (along line CD);

(d) $E_x = -\frac{\Delta V}{\Delta X} = 0$ and $E_y = -\frac{\Delta V}{\Delta Y} = 0$ at points A and B;

(e) $E_x = -\frac{\Delta V}{\Delta X} = 0$ along line AB;

(f) $E_y = -\frac{\Delta V}{\Delta Y} = 0$ along lines BC, CD, and AD.

The boundary conditions greatly simplify equation (35) along the lines AB, BC, AD, and CD and, in fact, make the calculation of simultaneous solutions to equations (30) and (35) possible. Along the lines AB, BC, AD, and CD, α and β reduce to the following expressions:

$$\alpha_{AB} = \frac{\varepsilon_0(2a_x b_0 E_{0y} - a_x b_3 E_{0y})}{2a_x a_y b_0} , \qquad (36)$$

$$\alpha_{BC} = \alpha_{AD} = \alpha_{CD} = \frac{\varepsilon_0(2a_y b_0 E_{0x} - a_y b_2 E_{0x})}{2a_x a_y b_0} , \qquad (37)$$

$$\beta_{AB} = \frac{\varepsilon_0 E_{0y}\rho_3}{a_y} , \qquad (38)$$

and

$$\beta_{BC} = \beta_{AD} = \beta_{CD} = \frac{\varepsilon_0 E_{0x}\rho_2}{a_x} . \qquad (39)$$

In order to initiate the numerical procedure which finds the simultaneous solutions to equations (30) and (35), it is necessary to make initial estimates of the values of the electric potential at all grid points and the space charge density for the corona region. The initial values of electric potential are estimated using equation (27) which is evaluated in subroutine CMAN. An initial estimate of the space charge density near the discharge electrode is obtained by assuming that the corona region is cylindrical and using continuity of current. This initial estimate is calculated from the expression

$$\rho_s = \frac{2\, S_y J_p}{\pi b_s r_w f\, (30\delta + 9\sqrt{\delta/r_w})} \times 10^{-3} , \qquad (40)$$

where ρ_s = space charge density at the outer boundary of the ionized sheath (coul/m^3),

S_y = one-half wire-to-wire spacing (m),

J_p = average current density at the plate (A/m^2),

b_s = effective charge carrier mobility at the outer boundary of the ionized sheath (m^2/V-sec),

r_w = radius of the wire (cm),

f = roughness factor, and

δ = relative density of the gas.

The numerical procedure for finding the solutions to equations (30) and (35) consists of the following steps.

1. V is computed at every point in the integration grid using equation (27).

2. ρ is computed at every point in the integration grid from equations (35) and (40).

3. V is recomputed at every point in the integration grid using equation (30).

4. Steps 2 and 3 are repeated alternately until 1) the potential on the grid converges, 2) the dominant eigenvalue of the potential solution (the norm of the potential changes across the grid) has converged, or 3) 5 iterations have taken place. If the potential has not converged but either of the last 2 conditions

has been satisfied, the potential at every point on the grid is adjusted by a term based on the dominant eigenvalue and the process resumes at step 2. Convergence of the dominant eigenvalue is obtained when the value of the eigenvalue changes by less than 0.1% from the previous iteration. Convergence of the potential is obtained when the potential at each grid point changes by less than 0.001% from the previous iteration.

5. The computed current density (obtained using the relationship $J = -\rho \left(\frac{\Delta V}{\Delta x}\right) b$) is compared with the measured current density. If the computed and measured current densities do not agree within 1%, then the space charge representing the corona region is adjusted and steps 1 through 5 are repeated until agreement is obtained.

This procedure iterates on a grid of electric field and space charge density until convergence is obtained. The major approximation, and one that is seemingly unavoidable in practice, is the assumption that the motion of all charge carriers can, on the average, be described by a single effective mobility. The space charge introduced by the particulate present in flue gas would reduce the effective mobility. The procedure uses a reduced mobility which is calculated from equation (16) and is evaluated in subroutine SPCHG1. The reduction in mobility is limited to a value of 1×10^{-4} m^2/V-sec in order to prevent nonconvergence of the grid under certain conditions.

Figure 15 shows a detailed flow chart for this subroutine. Information which is transmitted between the main program and this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

UEQ - Effective charge carrier mobility (m^2/V-sec). Limited to a lower value of 1×10^{-4} m^2/V-sec.

CD - Average current density at the plate (A/m^2).

AC - Radius of discharge electrode (m).

VO - Electric potential at the wire (V).

SX - Wire-to-plate spacing (m).

SY - One-half wire-to-wire spacing (m).

NX - Number of grid points in the x-direction. Can not exceed a value of 15.

NY - Number of grid points in the y-direction. Can not exceed a value of 15.

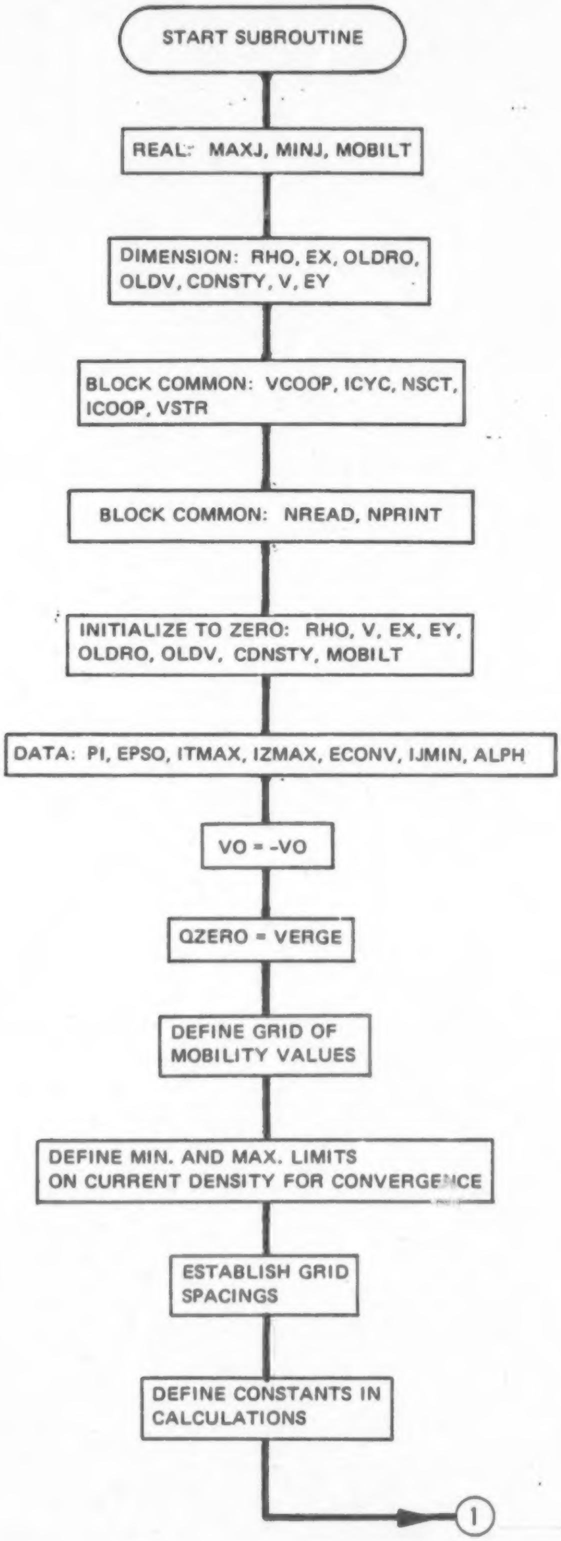
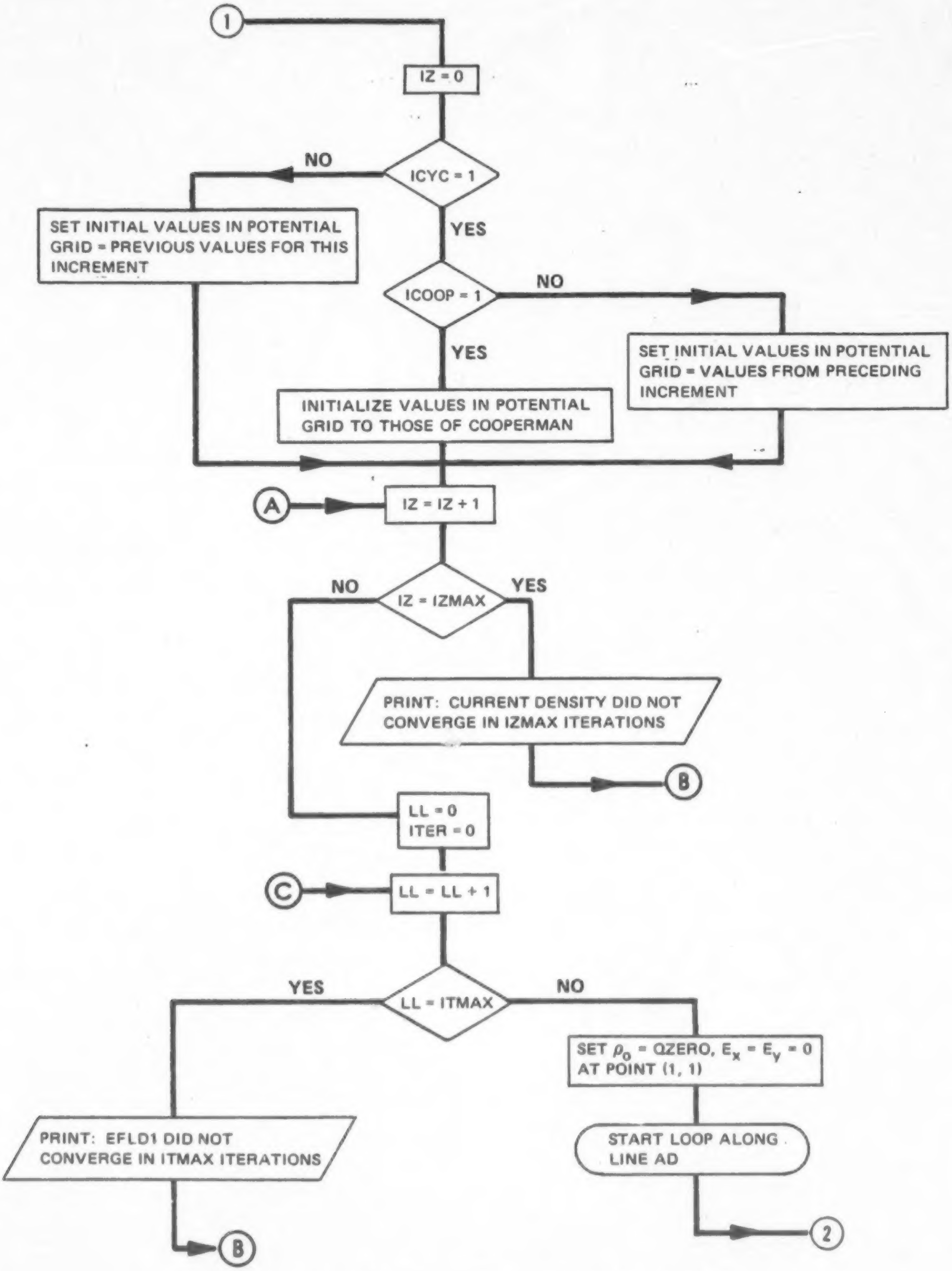

START SUBROUTINE
REAL: MAXJ, MINJ, MOBILT
DIMENSION: RHO, EX, OLDRO, OLDV, CDNSTY, V, EY
BLOCK COMMON: VCOOP, ICYC, NSCT, ICOOP, VSTR
BLOCK COMMON: NREAD, NPRINT
INITIALIZE TO ZERO: RHO, V, EX, EY, OLDRO, OLDV, CDNSTY, MOBILT
DATA: PI, EPSO, ITMAX, IZMAX, ECONV, IJMIN, ALPH
VO = -VO
QZERO = VERGE
DEFINE GRID OF MOBILITY VALUES
DEFINE MIN. AND MAX. LIMITS ON CURRENT DENSITY FOR CONVERGENCE
ESTABLISH GRID SPACINGS
DEFINE CONSTANTS IN CALCULATIONS
1

Figure 15. Flow chart for subroutine EFLD1 (Sheet 1 of 7).



①
IZ = 0
ICYC = 1
NO
YES
SET INITIAL VALUES IN POTENTIAL GRID = PREVIOUS VALUES FOR THIS INCREMENT
ICOOP = 1
NO
YES
SET INITIAL VALUES IN POTENTIAL GRID = VALUES FROM PRECEDING INCREMENT
INITIALIZE VALUES IN POTENTIAL GRID TO THOSE OF COOPERMAN
Ⓐ
IZ = IZ + 1
NO
IZ = IZMAX
YES
PRINT: CURRENT DENSITY DID NOT CONVERGE IN IZMAX ITERATIONS
Ⓑ
LL = 0
ITER = 0
Ⓒ
LL = LL + 1
YES
LL = ITMAX
NO
SET ρ_0 = QZERO, $E_x = E_y = 0$ AT POINT (1, 1)
PRINT: EFLD1 DID NOT CONVERGE IN ITMAX ITERATIONS
START LOOP ALONG LINE AD
Ⓑ
②

Figure 15. Flow chart for subroutine EFLD1 (Sheet 2 of 7).

2 OF 5

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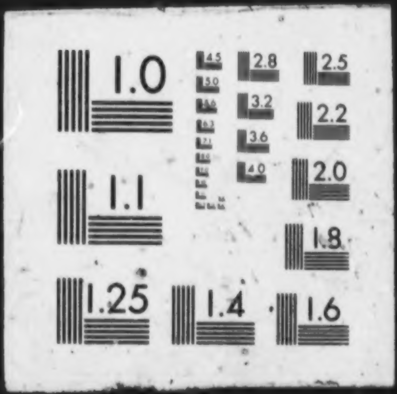

1.0
4.5
5.0
5.6
6.3
7.1
8.0
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

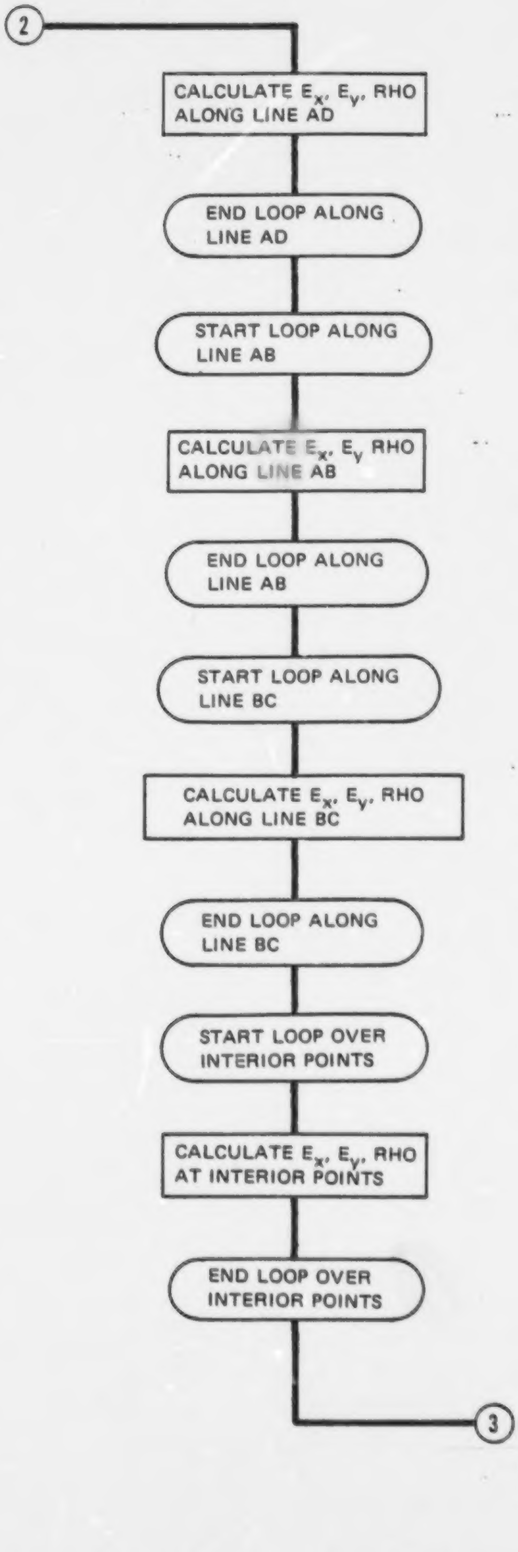

2
CALCULATE E_x, E_y, RHO ALONG LINE AD
END LOOP ALONG LINE AD
START LOOP ALONG LINE AB
CALCULATE E_x, E_y RHO ALONG LINE AB
END LOOP ALONG LINE AB
START LOOP ALONG LINE BC
CALCULATE E_x, E_y, RHO ALONG LINE BC
END LOOP ALONG LINE BC
START LOOP OVER INTERIOR POINTS
CALCULATE E_x, E_y, RHO AT INTERIOR POINTS
END LOOP OVER INTERIOR POINTS
3

Figure 15. Flow chart for subroutine EFLD1 (Sheet 3 of 7).

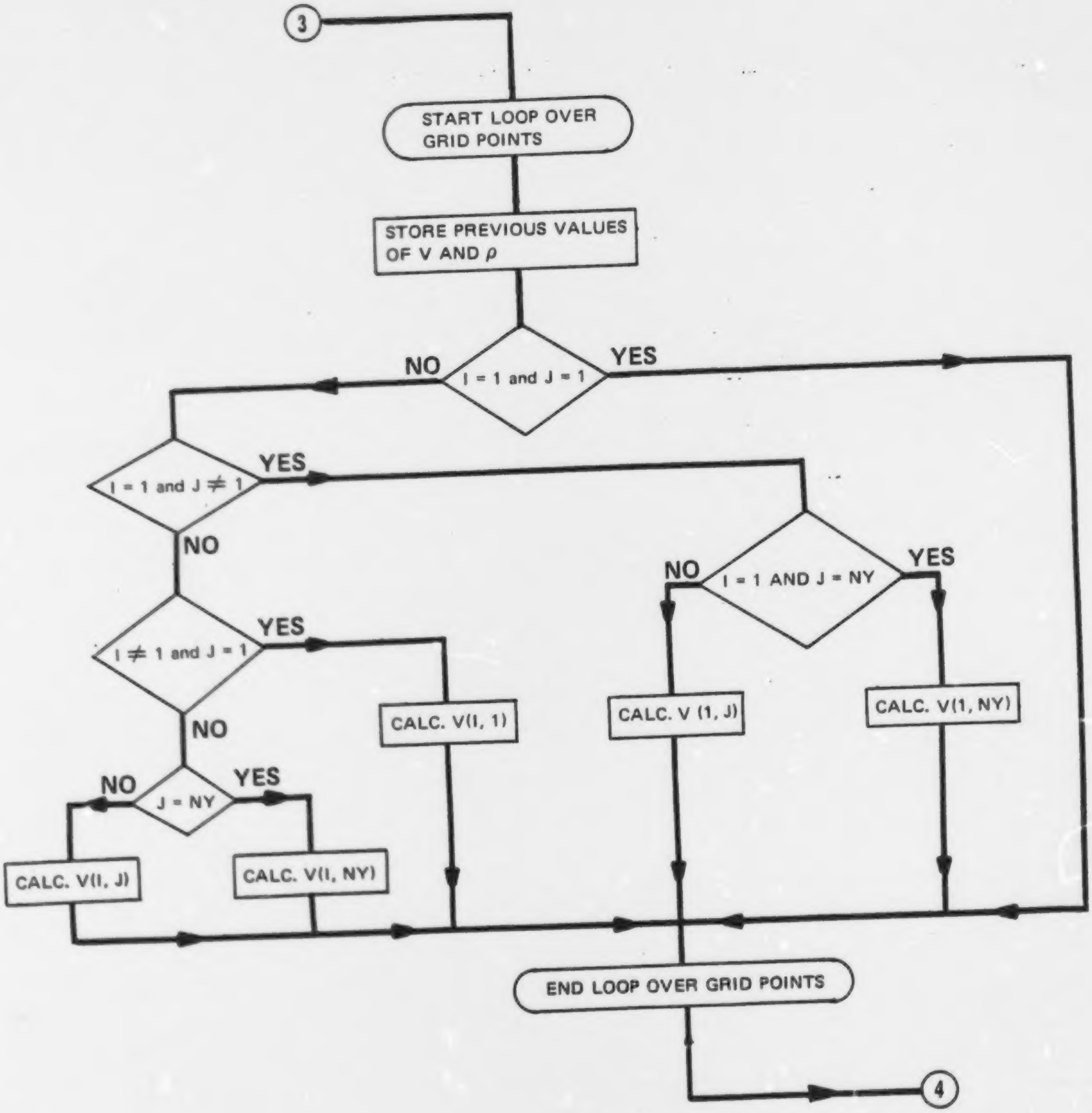

3
START LOOP OVER GRID POINTS
STORE PREVIOUS VALUES OF V AND ρ
I = 1 and J = 1
NO
YES
I = 1 and J ≠ 1
YES
NO
I = 1 AND J = NY
NO
YES
I ≠ 1 and J = 1
YES
NO
CALC. V(I, 1)
CALC. V (1, J)
CALC. V(1, NY)
J = NY
NO
YES
CALC. V(I, J)
CALC. V(I, NY)
END LOOP OVER GRID POINTS
4

Figure 15. Flow chart for subroutine EFLD1 (Sheet 4 of 7).

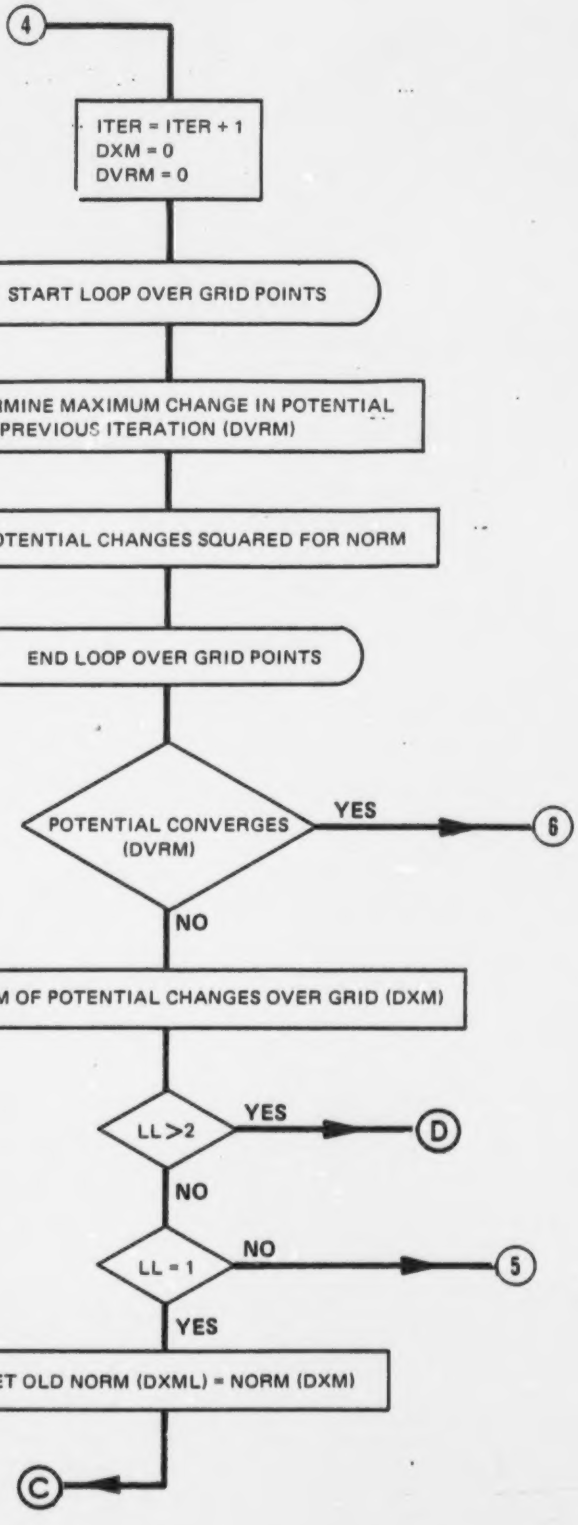

4
ITER = ITER + 1
DXM = 0
DVRM = 0
START LOOP OVER GRID POINTS
DETERMINE MAXIMUM CHANGE IN POTENTIAL FROM PREVIOUS ITERATION (DVRM)
SUM POTENTIAL CHANGES SQUARED FOR NORM
END LOOP OVER GRID POINTS
POTENTIAL CONVERGES (DVRM)
YES
6
NO
CALC. NORM OF POTENTIAL CHANGES OVER GRID (DXM)
LL>2
YES
D
NO
LL = 1
NO
5
YES
SET OLD NORM (DXML) = NORM (DXM)
C

Figure 15. Flow chart for subroutine EFLD1 (Sheet 5 of 7).

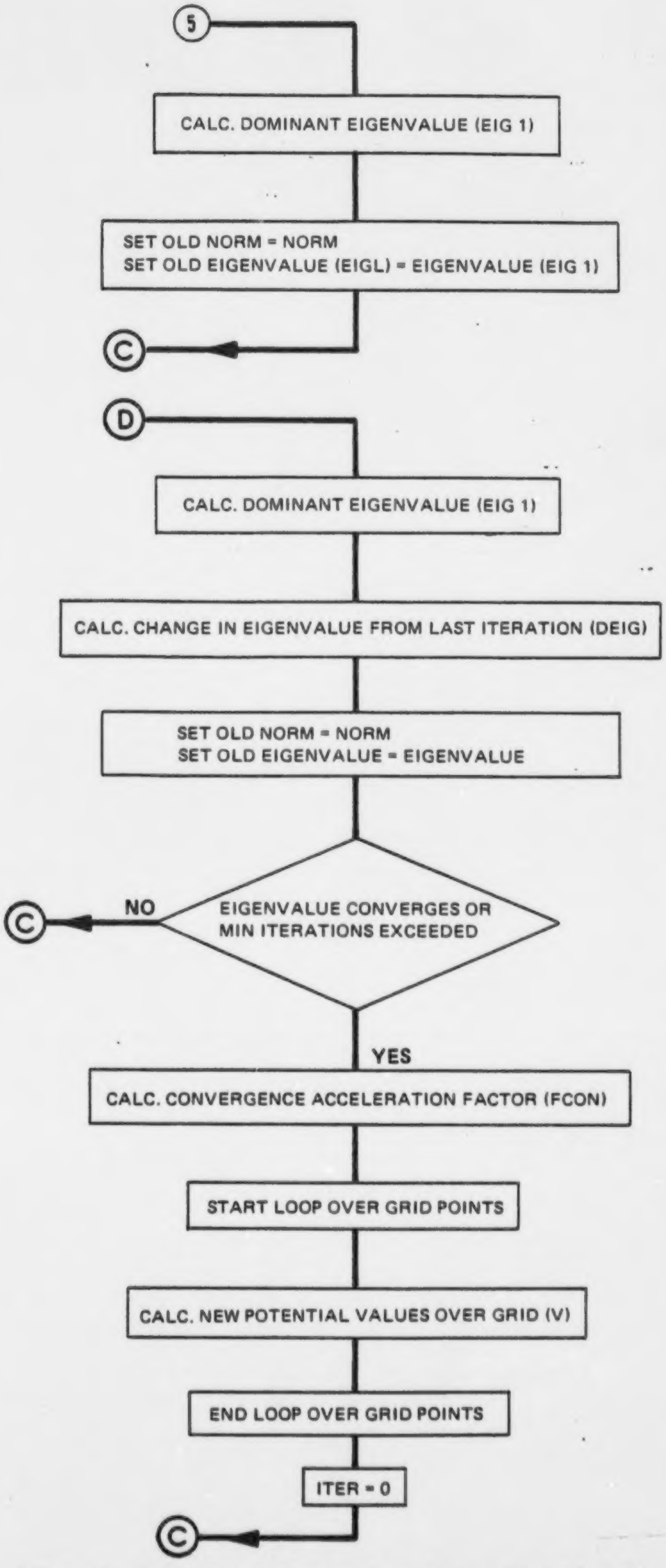

5
CALC. DOMINANT EIGENVALUE (EIG 1)
SET OLD NORM = NORM
SET OLD EIGENVALUE (EIGL) = EIGENVALUE (EIG 1)
C
D
CALC. DOMINANT EIGENVALUE (EIG 1)
CALC. CHANGE IN EIGENVALUE FROM LAST ITERATION (DEIG)
SET OLD NORM = NORM
SET OLD EIGENVALUE = EIGENVALUE
C
NO
EIGENVALUE CONVERGES OR
MIN ITERATIONS EXCEEDED
YES
CALC. CONVERGENCE ACCELERATION FACTOR (FCON)
START LOOP OVER GRID POINTS
CALC. NEW POTENTIAL VALUES OVER GRID (V)
END LOOP OVER GRID POINTS
ITER = 0
C

Figure 15. Flow chart for subroutine EFLD1 (Sheet 6 of 7).

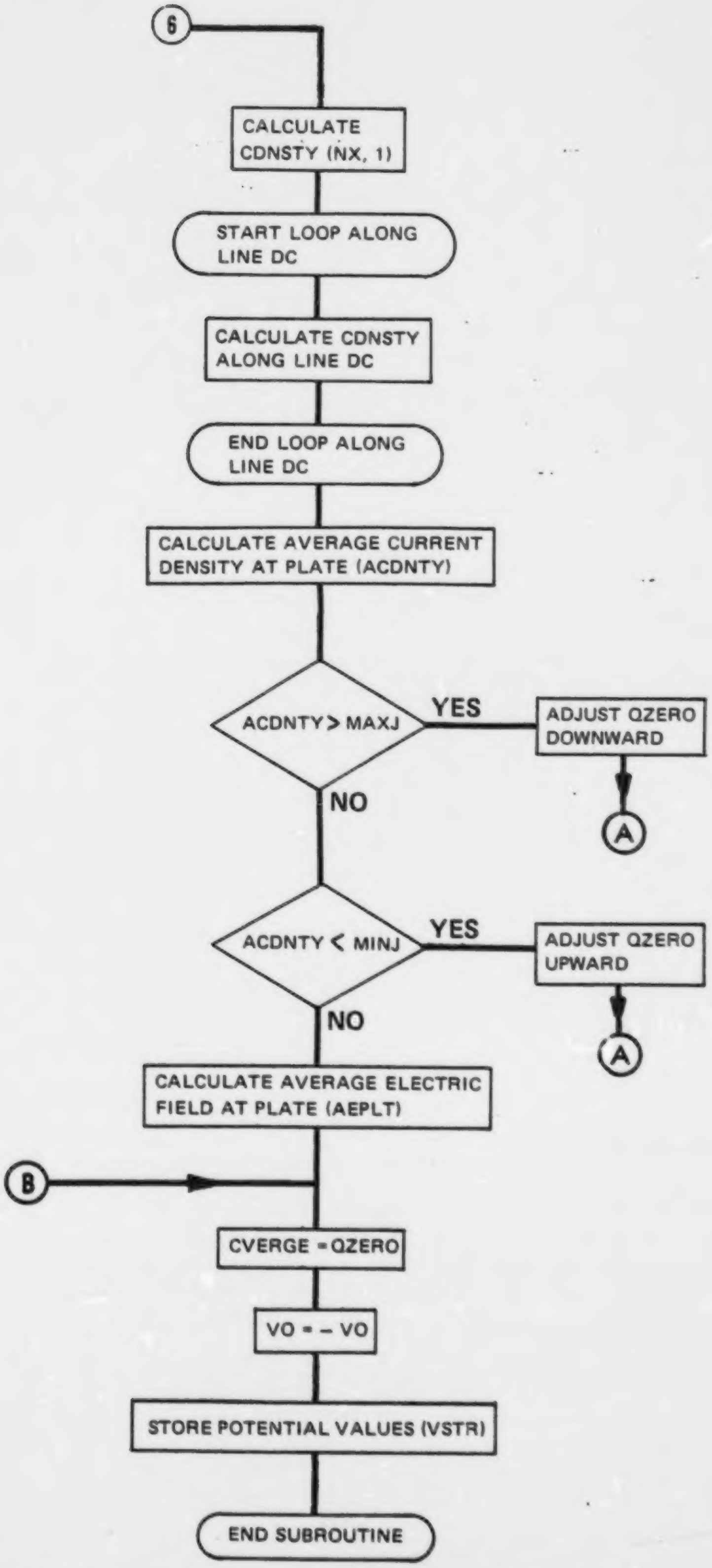

6
CALCULATE CDNSTY (NX, 1)
START LOOP ALONG LINE DC
CALCULATE CDNSTY ALONG LINE DC
END LOOP ALONG LINE DC
CALCULATE AVERAGE CURRENT DENSITY AT PLATE (ACDNTY)
ACDNTY > MAXJ
YES
ADJUST QZERO DOWNWARD
A
NO
ACDNTY < MINJ
YES
ADJUST QZERO UPWARD
A
NO
CALCULATE AVERAGE ELECTRIC FIELD AT PLATE (AEPLT)
B
CVERGE = QZERO
VO = – VO
STORE POTENTIAL VALUES (VSTR)
END SUBROUTINE

Figure 15. Flow chart for subroutine EFLD1 (Sheet 7 of 7).

TDK - Temperature of the gas (°K).

P - Pressure of the gas (atm).

AEPLT - Average electric field at the plate (V/m).

VERGE - Initial estimate of space charge density at the wire (coul/m^3).

CVERGE - Final value of space charge density at the wire for convergence (coul/m^3).

The following is a list of the necessary variables which are in common with the main program.

VCOOP(I,J) - Initial estimate of potential at points in the grid (V). I and J can not exceed a value of 15.

ICYC - Indicator which, with ICOOP, specifies which initial values are used for the potential grid.

NSCT - Increment counter.

ICOOP - Indicator which, with ICYC, specifies which initial values are used for the potential grid.

VSTR(I,J,NSCT) - Storage register for the potential values V(I,J) from each increment.

NPRNT - Indicator which specifies the unit number of the printer.

Of the above variables, the values of the following must be provided by the main program: UEQ, CD, AC, VO, SX, SY, NX, NY, TDK, P, VERGE, VCOOP, ICYC, NSCT, ICOOP, and NPRNT. AEPLT, CVERGE, and VSTR are determined in the subroutine. If convergence on the electric potential grid can not be obtained in 500 iterations, then a message stating that convergence can not be obtained is printed and the subroutine returns to the main program with those values which were calculated in the last iteration. If convergence on the average current density at the plate can not be obtained in 30 iterations, then a message stating that convergence can not be obtained is printed and the subroutine returns to the main program with those values which were calculated in the last iteration.

Subroutine EFLD2

This subroutine calculates a voltage-current curve up to a specified value of operating applied voltage and calculates the average electric field at the plate for the operating applied voltage. The voltage-current curve is generated by (1) specifying a starting value of average current density at the plate,

(2) incrementing upward on the average current density, and (3) determining the applied voltage at each value of current density. Once a value of current density results in an applied voltage which exceeds the specified operating applied voltage, an interpolation is performed in order to obtain the operating applied voltage and current density. At the operating applied voltage, calculations can also be made to give the average current density, average electric field, and average electric field at the plate in subincremental lengths.

The equations which are solved and the mathematical technique which is used to solve these equations are the same as discussed for subroutine EFLD1. The major differences in the two subroutines are the use of different boundary conditions in solving equations (30) and (35) and an added loop in EFLD2 which runs over values of average current density at the plate.

The boundary conditions imposed on the solutions to equations (30) and (35) are:

(1) J_p = given average current density at the plate;

(2) $\rho = \rho_s$, space charge density near the wire and hence,

$\rho = \rho_s = \rho_w$ at point A for calculations outside of r_s;

(3) $E_s r_s = E_c r_w$ = constant;

(4) $E_x = -\frac{\Delta V}{\Delta x} = 0$ and $E_y = -\frac{\Delta V}{\Delta y} = 0$ at points A and B;

(5) V = 0 on the plate or along line CD;

(6) $E_x = -\frac{\Delta V}{\Delta x} = 0$ along line AB;

(7) $E_y = -\frac{\Delta V}{\Delta y} = 0$ along lines BC, CD, and AD;

where r_s = radius of the ionized sheath (m),

E_s = electric field at the outer radius of the ionized sheath (V/m),

E_c = corona starting electric field (V/m), and

r_w = radius of the corona wire (m).

By using the above boundary conditions, solutions to equations (30) and (35) can be obtained without measured or known data.

The steps in the numerical procedure are outlined as follows:

1. Choose an average current density at the plate which corresponds to the lowest value desired on a current-voltage curve.

2. Estimate the potential at the wire that would produce the chosen value of average current density at the plate and calculate V at every point in the grid using equation (27).

3. Calculate ρ at every point in the grid using equation (35), where the space charge density at the wire is given by equation (40).

4. Recalculate V at every point in the grid using equation (30).

5. Steps 3 and 4 are repeated alternatively until 1) the potential on the grid converges, 2) the dominant eigenvalue of the potential solution (the norm of the potential changes across the grid) has converged, or 3) 5 iterations have taken place. If the potential has not converged but either of the last 2 conditions has been satisfied, the potential at every point on the grid is adjusted by a term based on the dominant eigenvalue and the process resumes at step 2. Convergence of the dominant eigenvalue is obtained when the value of the eigenvalue changes by less than 0.1% from the previous iteration. Convergence of the potential is obtained when the potential at each grid point changes by less than 0.001% from the previous iteration.

6. Check to see if the computed average current density at the plate equals the chosen value. If they agree, then the solution has been obtained. If they do not agree, adjust the potential at the wire and start the calculation over at step (3) above.

7. Choose a larger value of average current density at the plate and obtain a new solution by starting at step (3) with the existing potential grid used to estimate the actual potential grid.

8. Repeat steps (3)-(7) until the desired current-voltage curve is obtained.

In the above procedure, the electric potential at the wire is adjusted until solutions are found which satisfy equations (30) and (35) and the boundary conditions, whereas, in EFLD1, the space charge density at the wire is adjusted.

Figure 16 shows a detailed flow chart for this subroutine. Information which is transmitted between the main program and this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

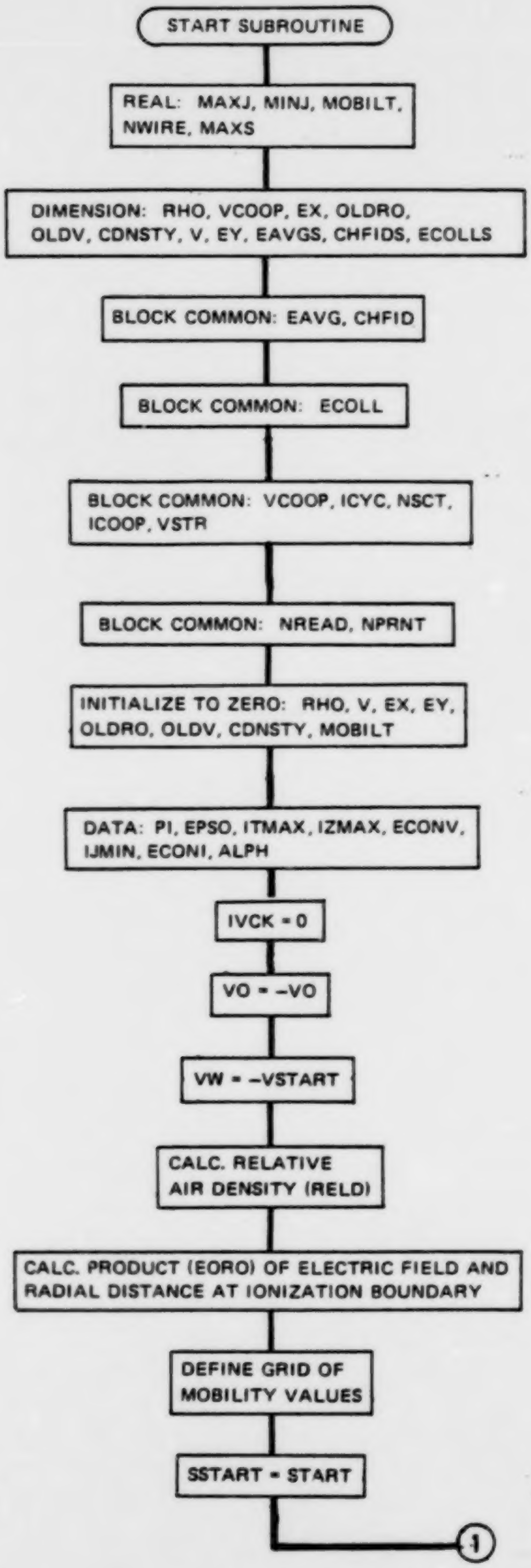

START SUBROUTINE
REAL: MAXJ, MINJ, MOBILT, NWIRE, MAXS
DIMENSION: RHO, VCOOP, EX, OLDRO, OLDV, CDNSTY, V, EY, EAVGS, CHFIDS, ECOLLS
BLOCK COMMON: EAVG, CHFID
BLOCK COMMON: ECOLL
BLOCK COMMON: VCOOP, ICYC, NSCT, ICOOP, VSTR
BLOCK COMMON: NREAD, NPRNT
INITIALIZE TO ZERO: RHO, V, EX, EY, OLDRO, OLDV, CDNSTY, MOBILT
DATA: PI, EPSO, ITMAX, IZMAX, ECONV, IJMIN, ECONI, ALPH
IVCK = 0
VO = –VO
VW = –VSTART
CALC. RELATIVE AIR DENSITY (RELD)
CALC. PRODUCT (EORO) OF ELECTRIC FIELD AND RADIAL DISTANCE AT IONIZATION BOUNDARY
DEFINE GRID OF MOBILITY VALUES
SSTART = START
1

Figure 16. Flow chart for subroutine EFLD2 (Sheet 1 of 12).

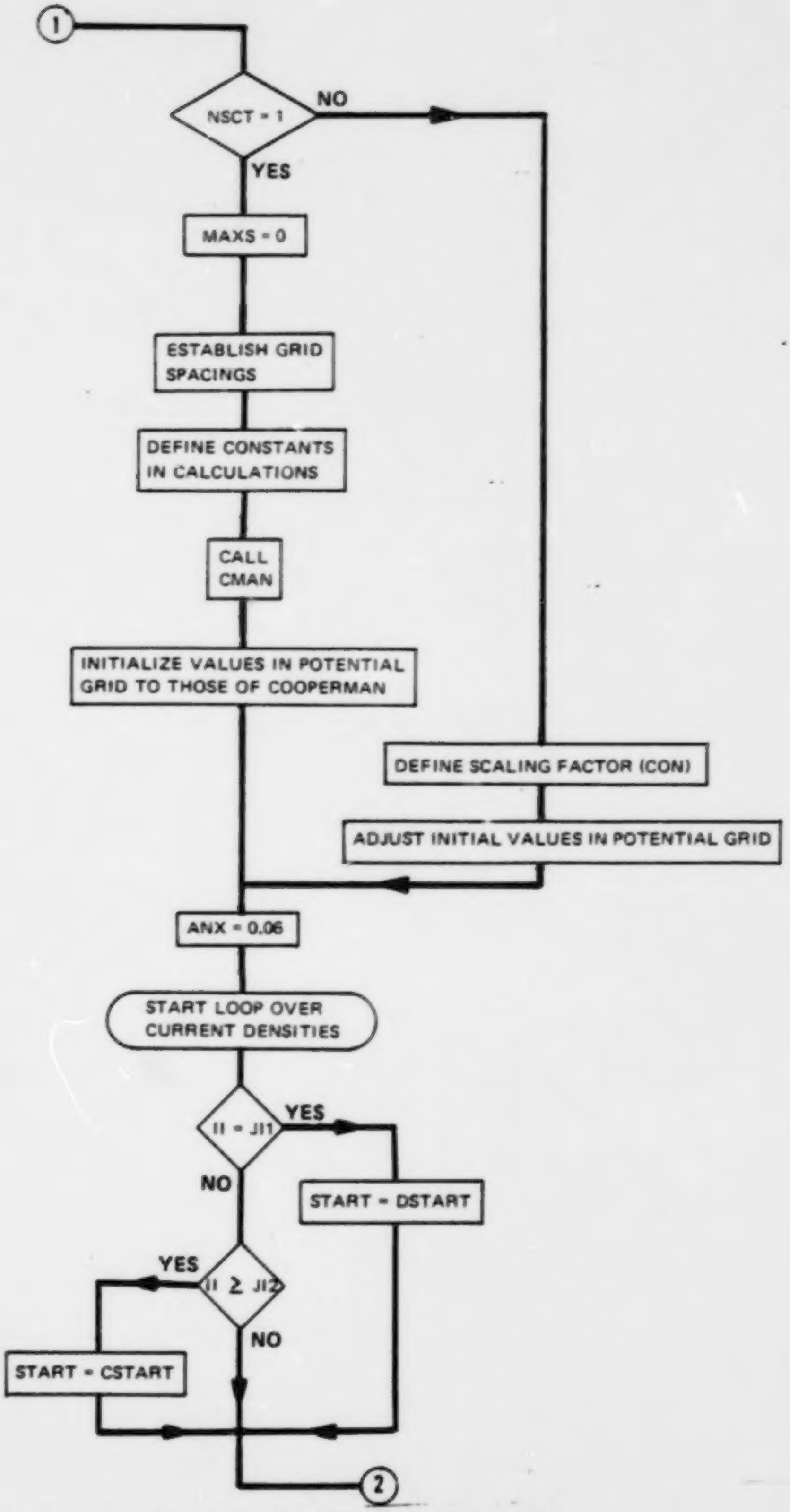

1
NSCT = 1
NO
YES
MAXS = 0
ESTABLISH GRID SPACINGS
DEFINE CONSTANTS IN CALCULATIONS
CALL CMAN
INITIALIZE VALUES IN POTENTIAL GRID TO THOSE OF COOPERMAN
DEFINE SCALING FACTOR (CON)
ADJUST INITIAL VALUES IN POTENTIAL GRID
ANX = 0.06
START LOOP OVER CURRENT DENSITIES
II = JI1
YES
NO
START = DSTART
YES
II ≥ JI2
NO
START = CSTART
2

Figure 16. Flow chart for subroutine EFLD2 (Sheet 2 of 12).

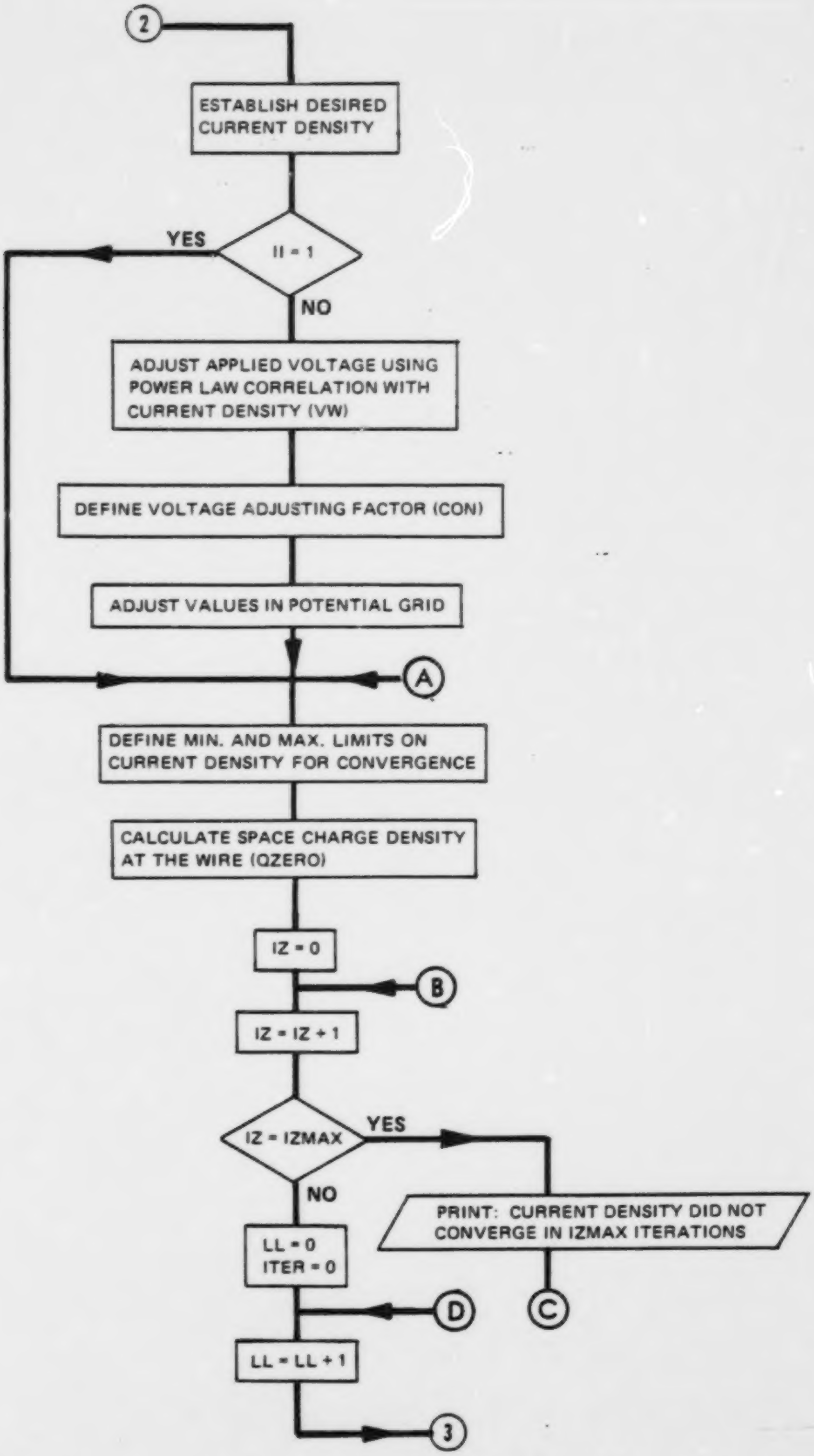

2
ESTABLISH DESIRED CURRENT DENSITY
YES
II = 1
NO
ADJUST APPLIED VOLTAGE USING POWER LAW CORRELATION WITH CURRENT DENSITY (VW)
DEFINE VOLTAGE ADJUSTING FACTOR (CON)
ADJUST VALUES IN POTENTIAL GRID
A
DEFINE MIN. AND MAX. LIMITS ON CURRENT DENSITY FOR CONVERGENCE
CALCULATE SPACE CHARGE DENSITY AT THE WIRE (QZERO)
IZ = 0
B
IZ = IZ + 1
IZ = IZMAX
YES
NO
PRINT: CURRENT DENSITY DID NOT CONVERGE IN IZMAX ITERATIONS
LL = 0
ITER = 0
D
C
LL = LL + 1
3

Figure 16. Flow chart for subroutine EFLD2 (Sheet 3 of 12).

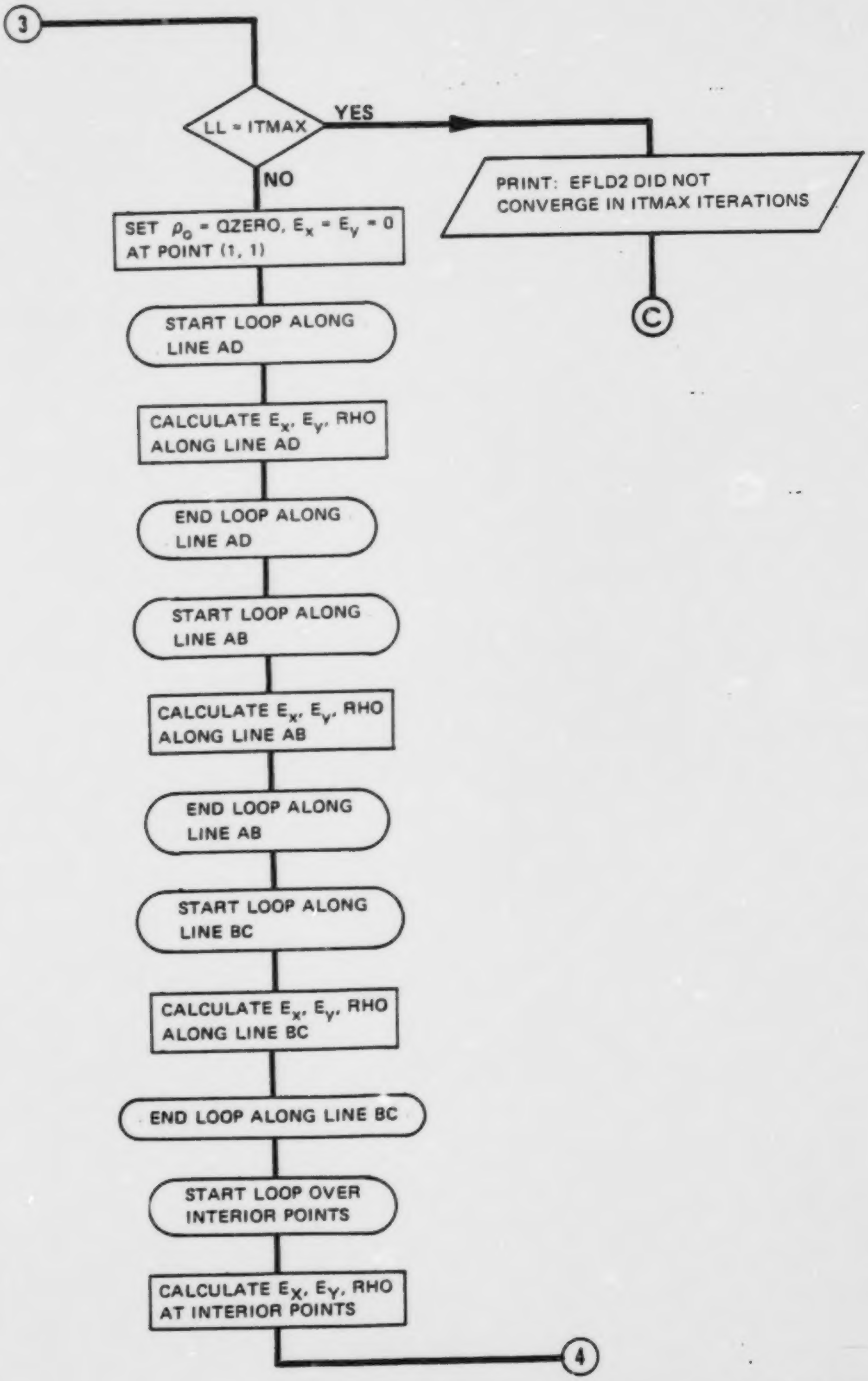

3
LL = ITMAX
YES
NO
PRINT: EFLD2 DID NOT CONVERGE IN ITMAX ITERATIONS
C
SET ρ_0 = QZERO, $E_x = E_y = 0$ AT POINT (1, 1)
START LOOP ALONG LINE AD
CALCULATE E_x, E_y, RHO ALONG LINE AD
END LOOP ALONG LINE AD
START LOOP ALONG LINE AB
CALCULATE E_x, E_y, RHO ALONG LINE AB
END LOOP ALONG LINE AB
START LOOP ALONG LINE BC
CALCULATE E_x, E_y, RHO ALONG LINE BC
END LOOP ALONG LINE BC
START LOOP OVER INTERIOR POINTS
CALCULATE E_X, E_Y, RHO AT INTERIOR POINTS
4

Figure 16. Flow chart for subroutine EFLD2 (Sheet 4 of 12).

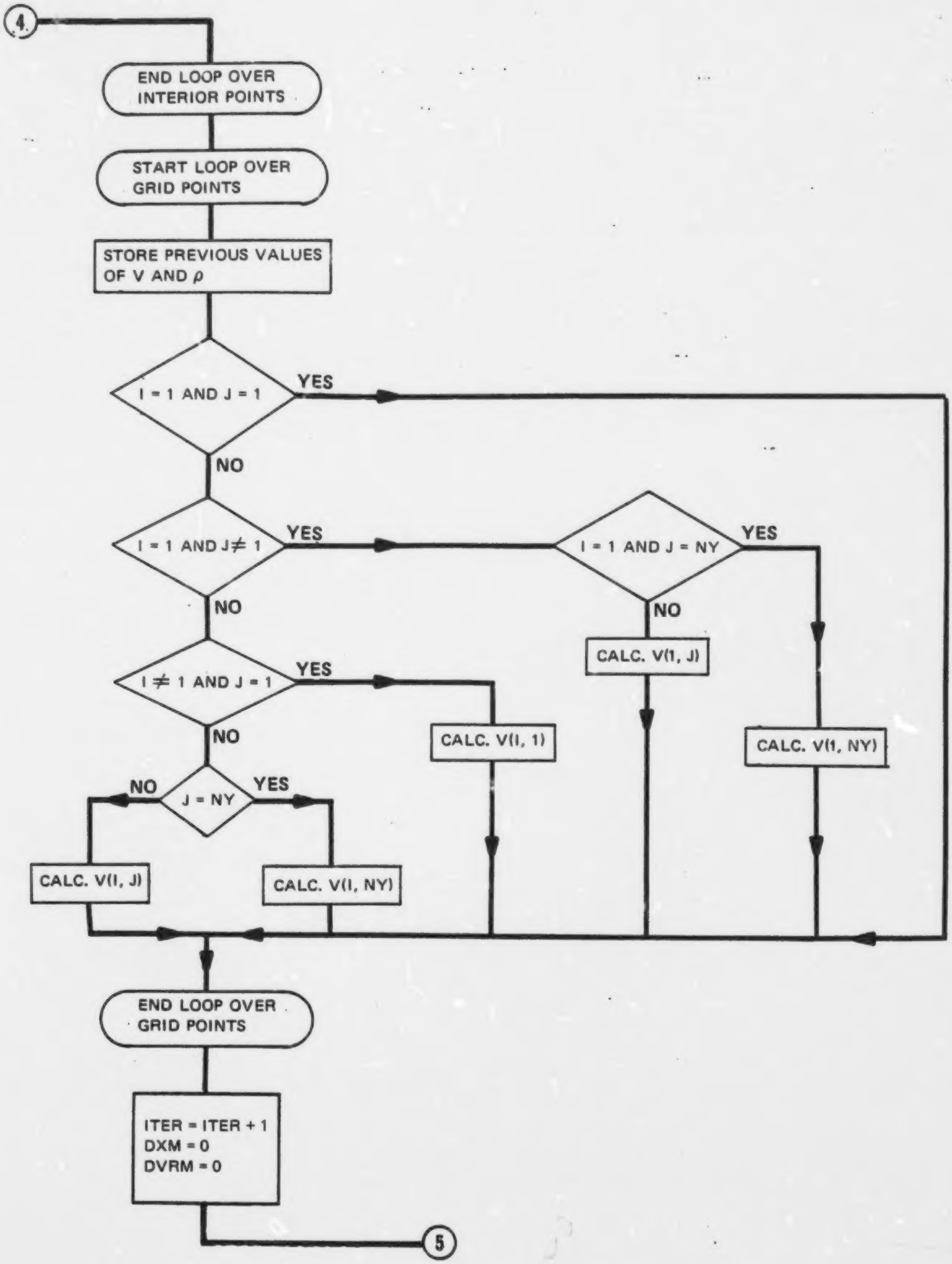

4
END LOOP OVER INTERIOR POINTS
START LOOP OVER GRID POINTS
STORE PREVIOUS VALUES OF V AND ρ
I = 1 AND J = 1
YES
NO
I = 1 AND J ≠ 1
YES
NO
I = 1 AND J = NY
YES
NO
CALC. V(1, J)
I ≠ 1 AND J = 1
YES
NO
CALC. V(I, 1)
CALC. V(1, NY)
J = NY
NO
YES
CALC. V(I, J)
CALC. V(I, NY)
END LOOP OVER GRID POINTS
ITER = ITER + 1
DXM = 0
DVRM = 0
5

Figure 16. Flow chart for subroutine EFLD2 (Sheet 5 of 12).

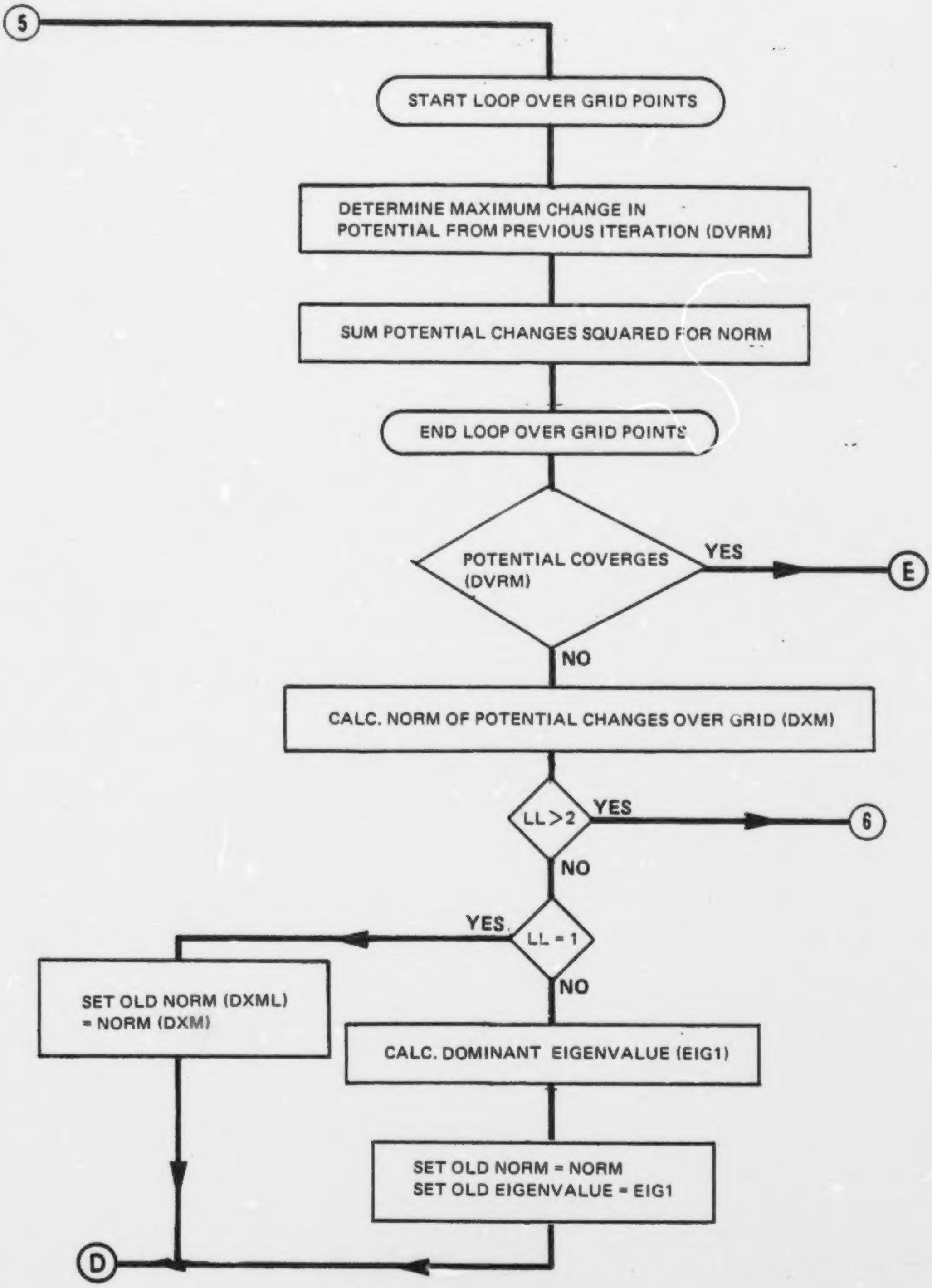

5
START LOOP OVER GRID POINTS
DETERMINE MAXIMUM CHANGE IN POTENTIAL FROM PREVIOUS ITERATION (DVRM)
SUM POTENTIAL CHANGES SQUARED FOR NORM
END LOOP OVER GRID POINTS
POTENTIAL COVERGES (DVRM)
YES
E
NO
CALC. NORM OF POTENTIAL CHANGES OVER GRID (DXM)
LL > 2
YES
6
NO
LL = 1
YES
NO
SET OLD NORM (DXML) = NORM (DXM)
CALC. DOMINANT EIGENVALUE (EIG1)
SET OLD NORM = NORM
SET OLD EIGENVALUE = EIG1
D

Figure 16. Flow chart for subroutine EFLD2 (Sheet 6 of 12).

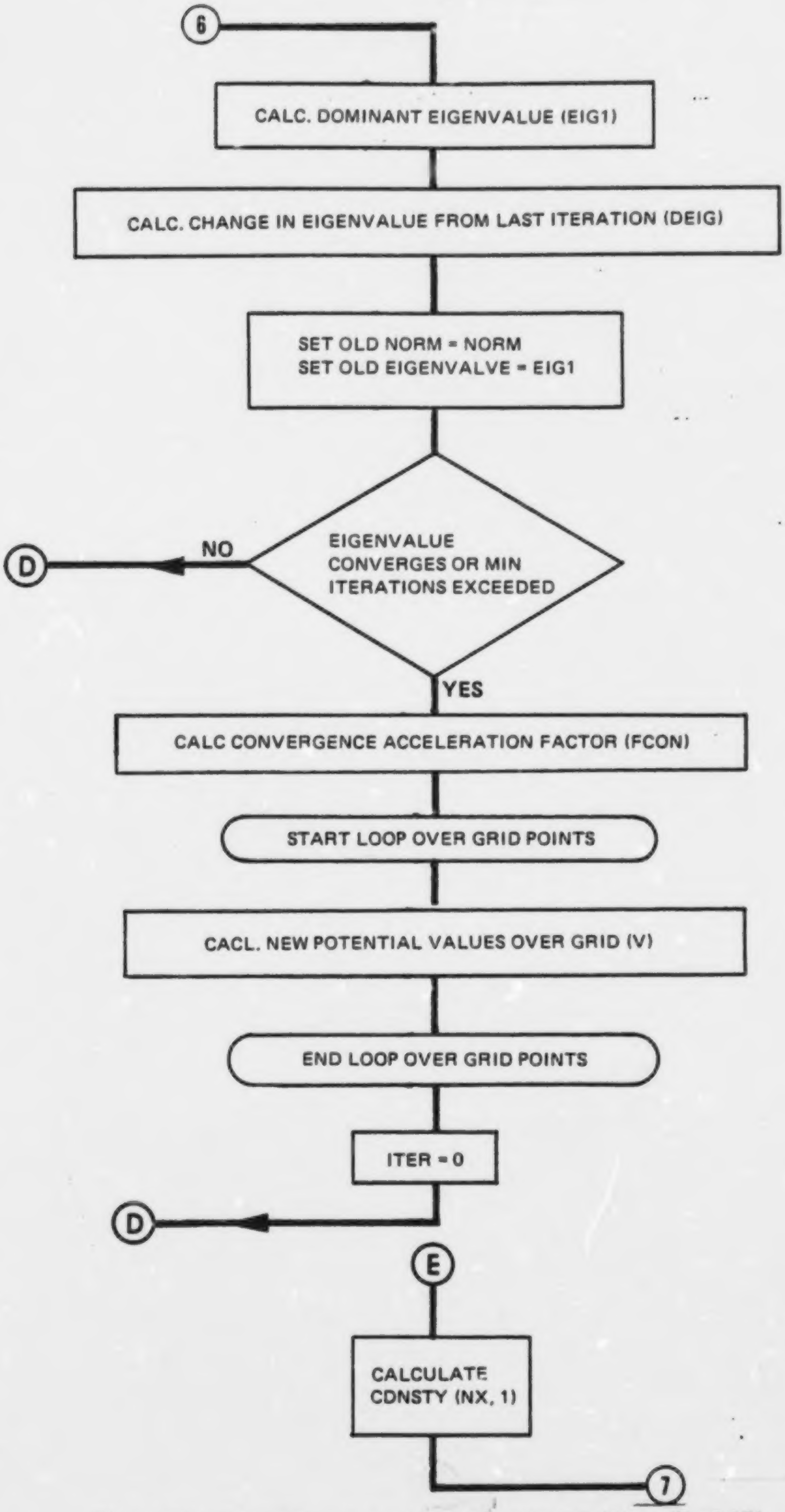

6
CALC. DOMINANT EIGENVALUE (EIG1)
CALC. CHANGE IN EIGENVALUE FROM LAST ITERATION (DEIG)
SET OLD NORM = NORM
SET OLD EIGENVALVE = EIG1
EIGENVALUE CONVERGES OR MIN ITERATIONS EXCEEDED
NO
D
YES
CALC CONVERGENCE ACCELERATION FACTOR (FCON)
START LOOP OVER GRID POINTS
CACL. NEW POTENTIAL VALUES OVER GRID (V)
END LOOP OVER GRID POINTS
ITER = 0
D
E
CALCULATE CDNSTY (NX, 1)
7

Figure 16. Flow chart for subroutine EFLD2 (Sheet 7 of 12).

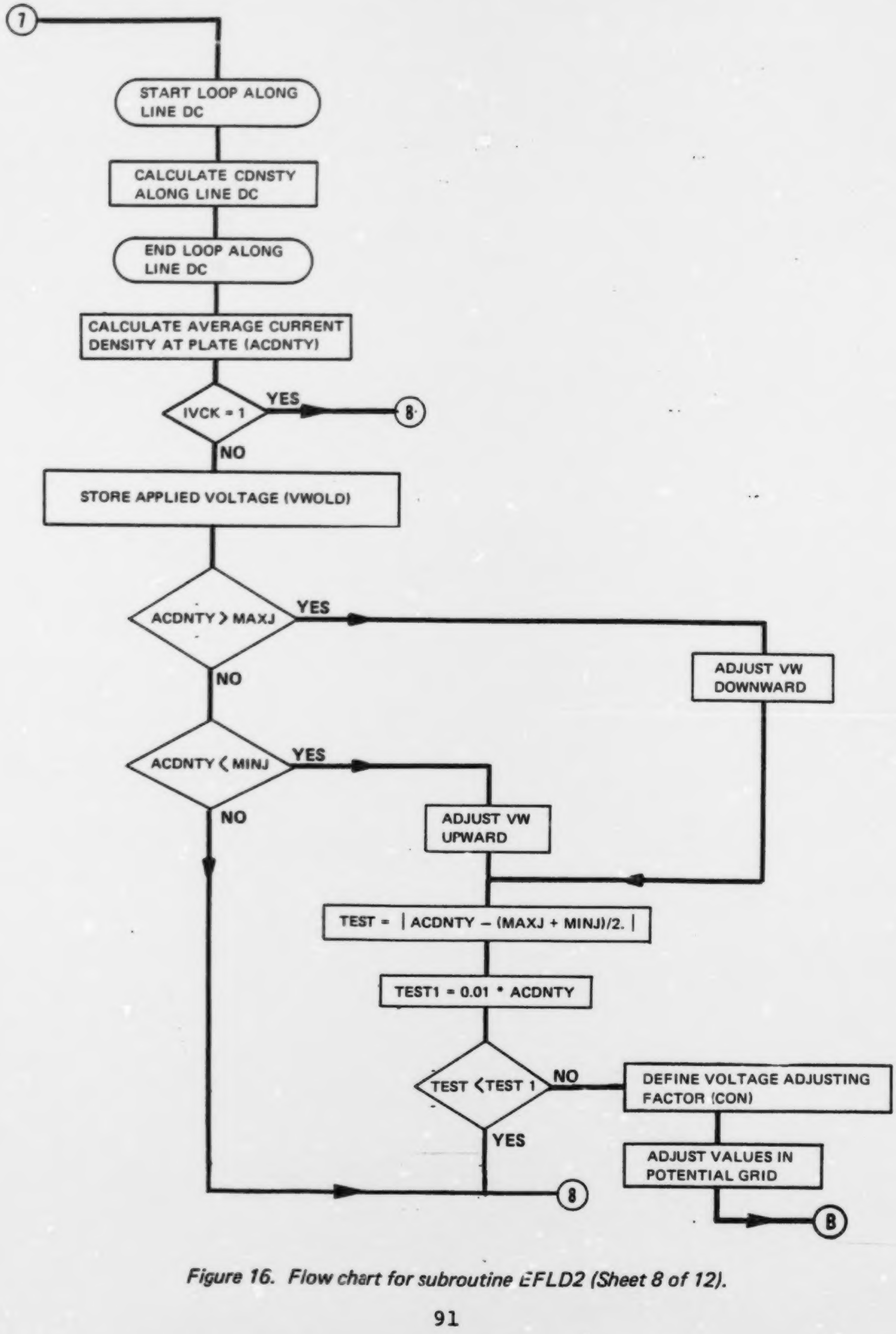

7
START LOOP ALONG LINE DC
CALCULATE CDNSTY ALONG LINE DC
END LOOP ALONG LINE DC
CALCULATE AVERAGE CURRENT DENSITY AT PLATE (ACDNTY)
IVCK = 1
YES
8
NO
STORE APPLIED VOLTAGE (VWOLD)
ACDNTY > MAXJ
YES
NO
ADJUST VW DOWNWARD
ACDNTY < MINJ
YES
NO
ADJUST VW UPWARD
TEST = | ACDNTY – (MAXJ + MINJ)/2. |
TEST1 = 0.01 * ACDNTY
TEST < TEST 1
NO
YES
DEFINE VOLTAGE ADJUSTING FACTOR (CON)
ADJUST VALUES IN POTENTIAL GRID
8
B

Figure 16. Flow chart for subroutine EFLD2 (Sheet 8 of 12).

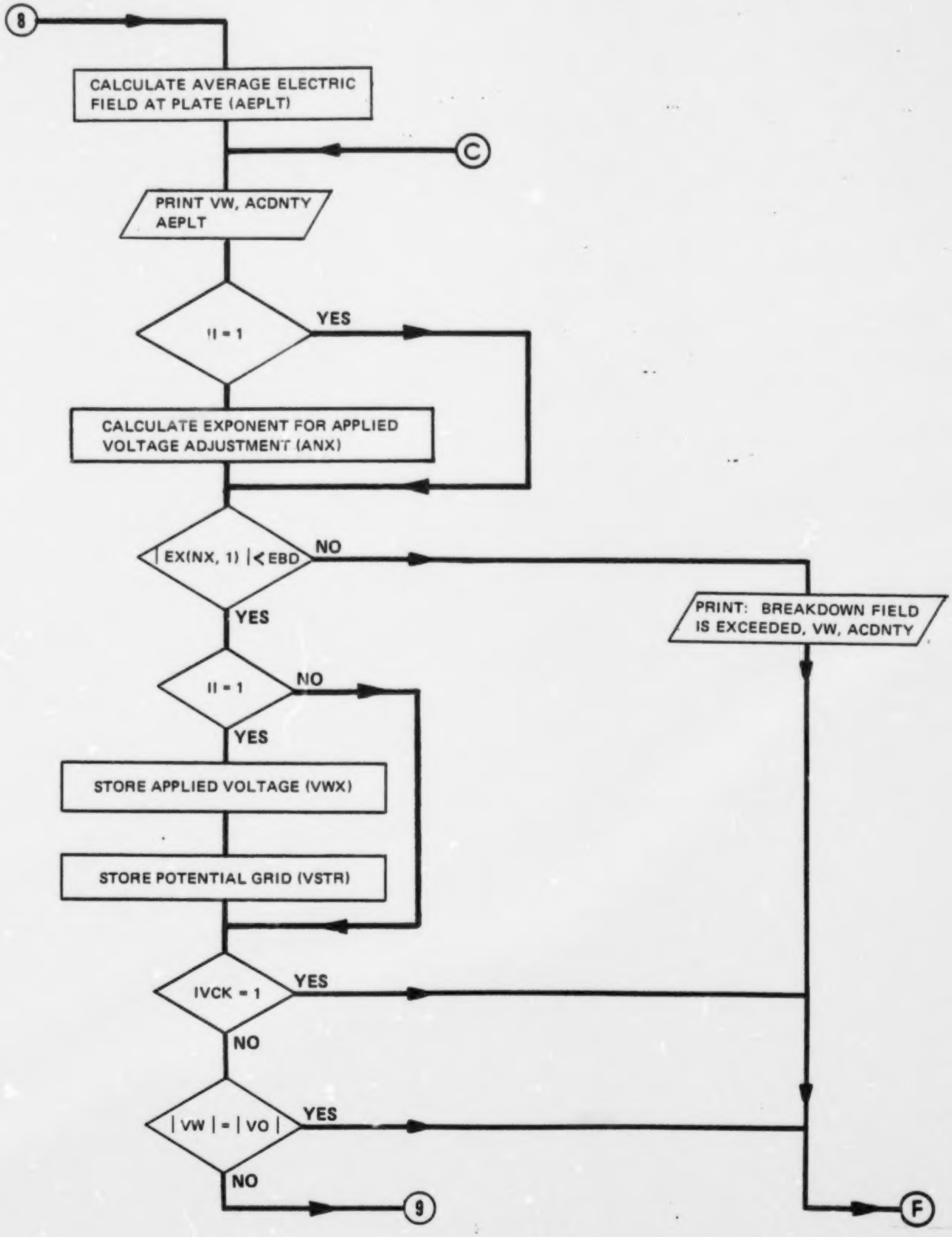

8
CALCULATE AVERAGE ELECTRIC FIELD AT PLATE (AEPLT)
C
PRINT VW, ACDNTY AEPLT
II = 1
YES
CALCULATE EXPONENT FOR APPLIED VOLTAGE ADJUSTMENT (ANX)
| EX(NX, 1) | < EBD
NO
PRINT: BREAKDOWN FIELD IS EXCEEDED, VW, ACDNTY
YES
II = 1
NO
YES
STORE APPLIED VOLTAGE (VWX)
STORE POTENTIAL GRID (VSTR)
IVCK = 1
YES
NO
| VW | = | VO |
YES
NO
9
F

Figure 16. Flow chart for subroutine EFLD2 (Sheet 9 of 12).

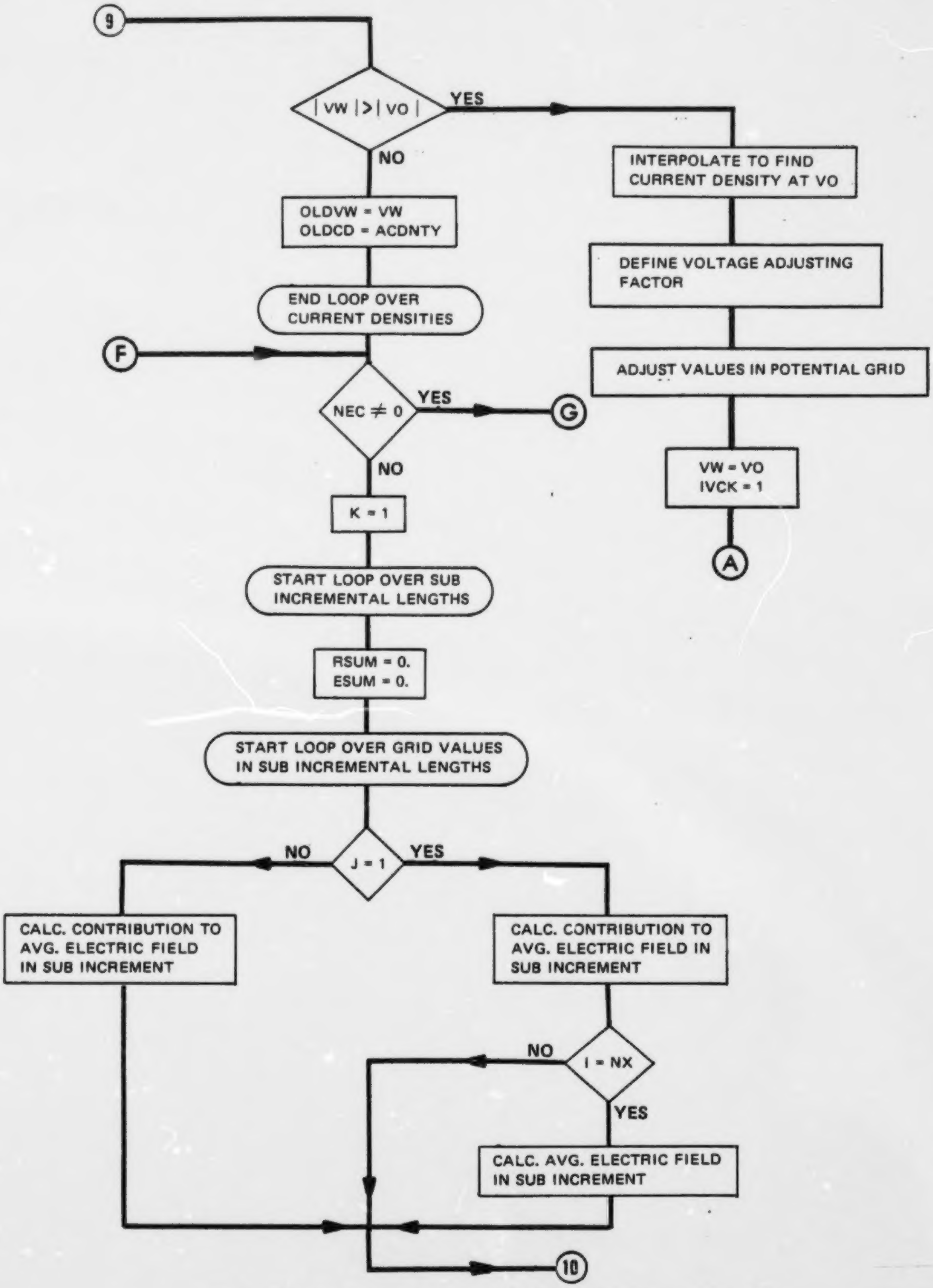

9
| VW | > | VO |
YES
NO
INTERPOLATE TO FIND CURRENT DENSITY AT VO
DEFINE VOLTAGE ADJUSTING FACTOR
ADJUST VALUES IN POTENTIAL GRID
VW = VO
IVCK = 1
A
OLDVW = VW
OLDCD = ACDNTY
END LOOP OVER CURRENT DENSITIES
F
NEC ≠ 0
YES
G
NO
K = 1
START LOOP OVER SUB INCREMENTAL LENGTHS
RSUM = 0.
ESUM = 0.
START LOOP OVER GRID VALUES IN SUB INCREMENTAL LENGTHS
NO
J = 1
YES
CALC. CONTRIBUTION TO AVG. ELECTRIC FIELD IN SUB INCREMENT
CALC. CONTRIBUTION TO AVG. ELECTRIC FIELD IN SUB INCREMENT
NO
I = NX
YES
CALC. AVG. ELECTRIC FIELD IN SUB INCREMENT
10

Figure 16. Flow chart for subroutine EFLD2 (Sheet 10 of 12).

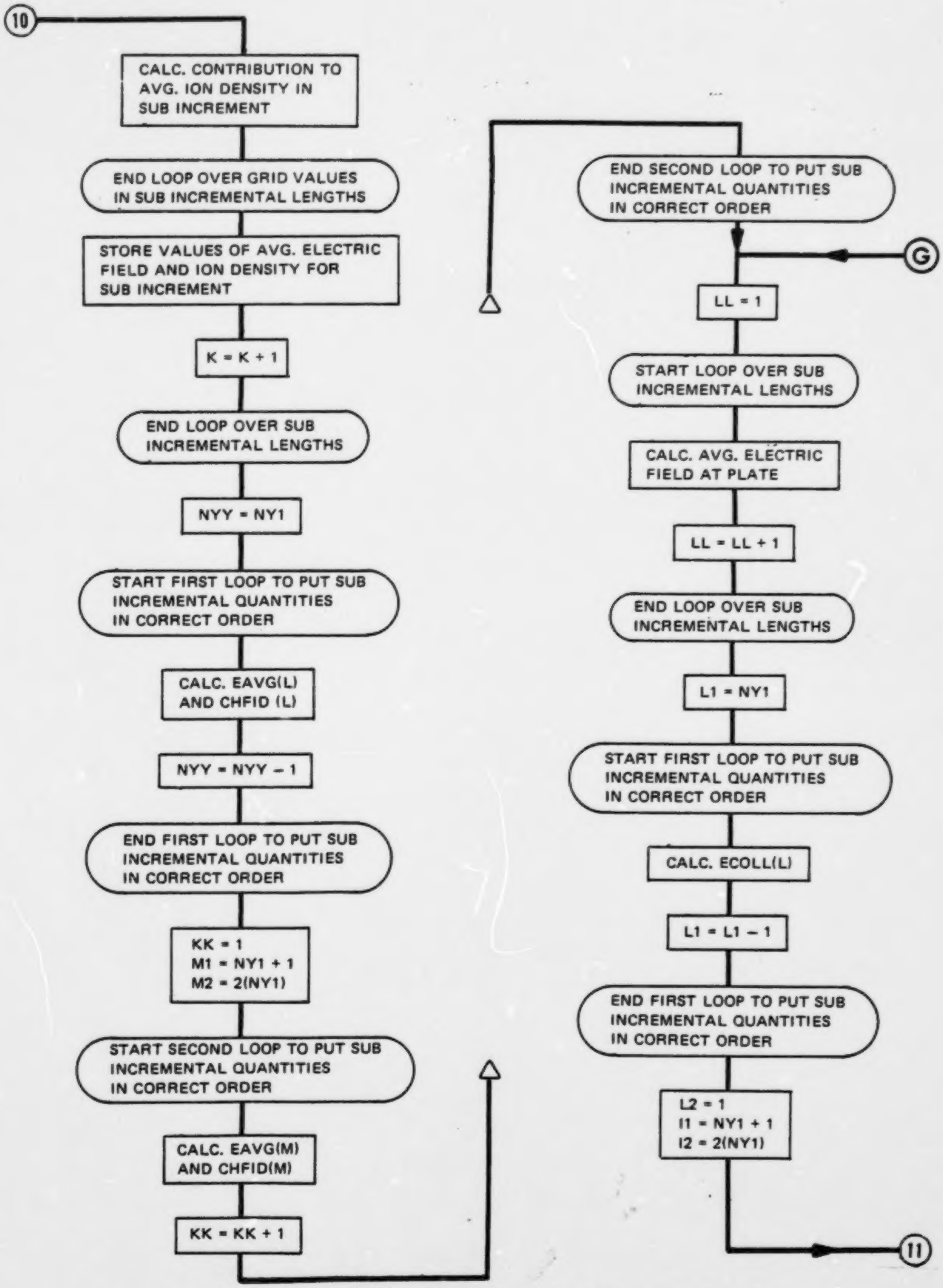
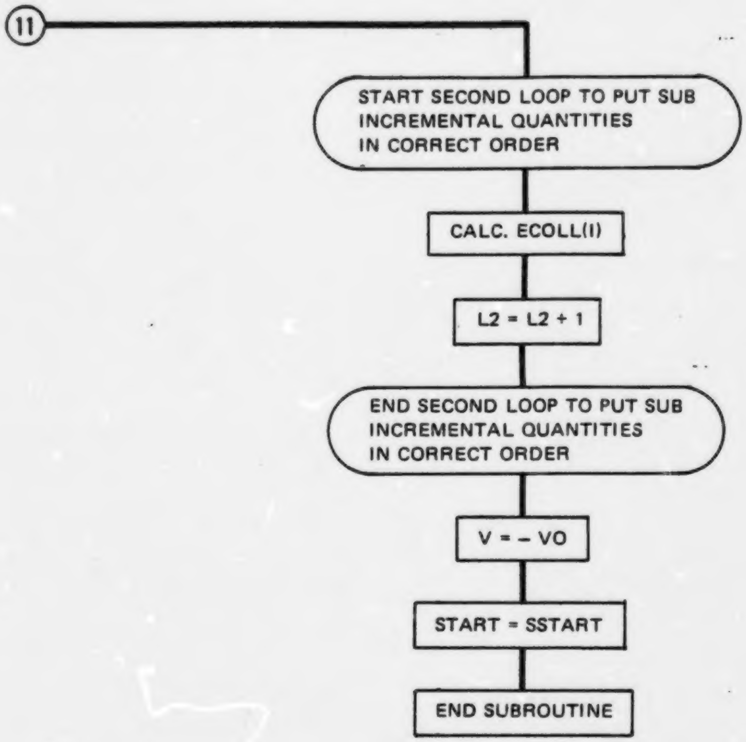

10
CALC. CONTRIBUTION TO AVG. ION DENSITY IN SUB INCREMENT
END LOOP OVER GRID VALUES IN SUB INCREMENTAL LENGTHS
STORE VALUES OF AVG. ELECTRIC FIELD AND ION DENSITY FOR SUB INCREMENT
K = K + 1
END LOOP OVER SUB INCREMENTAL LENGTHS
NYY = NY1
START FIRST LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
CALC. EAVG(L) AND CHFID (L)
NYY = NYY – 1
END FIRST LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
KK = 1
M1 = NY1 + 1
M2 = 2(NY1)
START SECOND LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
CALC. EAVG(M) AND CHFID(M)
KK = KK + 1
END SECOND LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
G
LL = 1
START LOOP OVER SUB INCREMENTAL LENGTHS
CALC. AVG. ELECTRIC FIELD AT PLATE
LL = LL + 1
END LOOP OVER SUB INCREMENTAL LENGTHS
L1 = NY1
START FIRST LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
CALC. ECOLL(L)
L1 = L1 – 1
END FIRST LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
L2 = 1
I1 = NY1 + 1
I2 = 2(NY1)
11

Figure 16. Flow chart for subroutine EFLD2 (Sheet 11 of 12).



11
START SECOND LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
CALC. ECOLL(I)
L2 = L2 + 1
END SECOND LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
V = – VO
START = SSTART
END SUBROUTINE

Figure 16. Flow chart for subroutine EFLD2 (Sheet 12 of 12).

UEQ - Effective charge carrier mobility (m^2/V-sec).

AC - Radius of discharge electrode (m).

VO - Chosen operating applied voltage (V).

SX - Wire-to-plate spacing (m).

SY - One-half wire-to-wire spacing (m).

NX - Number of grid points in the x-direction. Can not exceed a value of 15.

NY - Number of grid points in the y-direction. Can not exceed a value of 15.

AEPLT - Average electric field at the plate (V/m).

TDK - Temperature of the gas (°K).

P - Pressure of the gas (atm).

RF - Roughness factor for the discharge wire ($0.5 \leq RF \leq 1.0$).

START - Chosen initial current density at which the voltage-current curve calculation starts (A/m^2). Current densities increment in values of START until a change is specified.

DSTART - Chosen increment in current density which is used in place of START when specified (A/m^2).

CSTART - Chosen increment in current density which is used in place of DSTART when specified (A/m^2).

IFINAL - Indicator which terminates the loop over average current densities at the plate after IFINAL times.

VSTART - Initial estimate of applied voltage corresponding to first value of average current density at the plate on the voltage-current curve (V).

VW - Operating applied voltage corresponding to a given current density (V).

ACDNTY - Average current density at the plate (A/m^2).

NWIRE - Number of wires per gas passage per electrical section.

NEC - Indicator which governs the calculations of average current density, average electric field, and average electric field at the plate in subincremental lengths. The calculations are performed when NEC = 0 and are not performed when NEC = 1.

EBD - Electrical breakdown strength of the gas (V/m).

JI1 - Indicator which governs the change in the increment on average current density at the plate from START TO DSTART. The change occurs on the JIL-th value of current density.

JI2 - Indicator which governs the change in the increment on average current density at the plate from DSTART to CSTART. The change occurs on the JI2-th value of current density.

The following is a list of the variables which are in common with the main program.

EAVG(M) - Average electric field in a given subincrement of length (V/m). M cannot exceed the value of 30.

CHFID(M) - Average ion density in the absence of particles in a given subincrement of length ($\#/m^3$). M can not exceed a value of 30.

ECOLL(M) - Average electric field at the plate in a given subincrement of length (V/m). M can not exceed the value of 30.

VCOOP(I,J) - Initial estimate of potential at points in the grid (V). I and J can not exceed a value of 15.

ICYC - Indicator which, with ICOOP, specifies which initial values are used for the potential grid.

NSCT - Increment counter.

ICOOP - Indicator which, with ICYC, specifies which initial values are used for the potential grid.

VSTR(I,J,NSCT) - Storate register for the potential values V(I,J) from each increment.

NPRNT - Indicator which specifies the unit number of the printer.

Of the above variables, the values of the following must be provided by the main program: UEQ, AC, VO, SX, SY, NX, NY, TDK, P, RF, START, DSTART, CSTART, IFINAL, VSTART, NWIRE, NEC, EBD, JI1, JI2, ICYC, NSCT, ICOOP, and NPRNT. AEPLT, VW, ACDNTY, EAVG, CHFID, ECOLL, VSTR, and VCOOP are determined in the subroutine.

The subroutine calls subroutine CMAN in order to determine VCOOP.

If, for a given current density, convergence on the electric potential grid can not be obtained in 500 iterations, then a message stating that convergence can not be obtained is printed and those values which were calculated in the last iteration are used for that particular point on the voltage-current curve. If convergence on a given average current density at the plate can not be obtained in 30 iterations, then a message stating that convergence can not be obtained is printed and those values which were calculated in the last iteration are used for that particular point on the voltage-current curve.

There are three possible conditions which will result in termination of the voltage-current curve at a particular voltage and current. The curve is terminated if (1) the specified operating applied voltage is reached, or (2) the number of points on the curve is equal to value of IFINAL, or (3) the specified value of electrical breakdown strength near the collection electrode is exceeded. If the breakdown strength is exceeded, a message stating that this is the case is printed.

Subroutine CHARGN

This subroutine calculates particle charge as a function of residence time, electrical conditions, gas conditions, and particle characteristics. In order to use this subroutine, statement function RATE and subroutines ARCCOS and ZERO are required.

The subroutine determines particle charge by solving equation (12). Equation (12) is a first-order differential equation of the form

$$\frac{dy}{dx} = f(x,y) \tag{41}$$

with initial values x_0 and y_0 and is solved numerically using a quartic Runge-Kutta method.[33] This is a single-step method in which the value of y at $x = x_n$ is used to compute $y_{n+1} = y(x_{n+1})$ and earlier values y_{n-1}, y_{n-2}, etc. are not used.

The increment for advancing the dependent variable is given by

$$\Delta y = \frac{1}{6}\,(k_1 + 2k_2 + 2k_3 + k_4) \tag{42}$$

where, for a given stepsize h,

$$k_1 = hf(x_n, y_n) \quad , \tag{43}$$

$$k_2 = hf(x_n + \tfrac{1}{2}h, y_n + \tfrac{1}{2} k_1) \quad , \tag{44}$$

$$k_3 = hf(x_n + \tfrac{1}{2}h, y_n + \tfrac{1}{2} k_2) \quad , \tag{45}$$

and

$$k_4 = hf(x_n + h, y_n + k_3) \quad . \tag{46}$$

The values at (x_{n+1}, y_{n+1}) are given by

$$x_{n+1} = x_n + h \tag{47}$$

and

$$y_{n+1} = y_n + \Delta y \quad . \tag{48}$$

The subroutine calls the statement function RATE to calculate the right hand side of equation (12) at the function values specified in equations (42)-(46).

The numerical procedure for finding solutions to equation (12) consists of the following steps.

1. The initial conditions are taken to be $q = 0$ at $t = 0$.

2. q_s is calculated in the main program using equation (13) and is supplied to subroutine CHARGN and statement function RATE.

3. For each value of q required in the Runge-Kutta scheme, a value of θ_0 is calculated in statement function RATE using equation (14).

4. The integration over θ on the right hand side of equation (12) is performed in statement function RATE using Gaussian quadratures.[34] For each value of θ which is chosen for this integration, the radial distance (r_0) from the center of the particle and along θ for which the total electric field is zero is calculated using subroutine ZERO.

5. The three individual charging rates are calculated and then added in statement function RATE to give the total instantaneous charging rate for a particular value of q.

6. The total charging rates necessary for use in equations (42)-(46) are obtained by subroutine CHARGN and q is obtained from equation (48).

Figure 17 shows a detailed flow chart for this subroutine. All information which is transmitted between the main program and this subroutine is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

SCHARG - Value of saturation charge number from the field charging equation [see eq. (13)].

DCONST - Value of the quantity [$\frac{(K-1)}{(K+2)} a^3$] found in equation (12) [m^3].

EZERO - Applied electric field strength for particle charging (V/m).

V - Value of the quantity [$\frac{e^2}{4\pi\varepsilon_0 akT}$] found in equation (12).

RSIZE - Radius of the particle (m).

ECONST - Value of the quantity [$\frac{3eE_0 a}{kT(K+2)}$] found in equation (12).

RR - Value of the quantity [$\frac{eE_0}{kT}$] found in equation (12) [m^{-1}].

FACTOR - Value of the quantity [$\frac{\pi\tilde{v}a^2}{2}$] found in equation (12) [m^3/sec].

COEFF - Value of the quantity [$\frac{bq_s}{4\varepsilon_0}$] found in equation (12) [m^3/sec].

AFID - Free ion density for particle charging (#/m^3).

RATE - Statement function which must be supplied to subroutine CHARGN.

H - Increment size for Runge-Kutta integration (sec).

YI - Initial value of charge number.

NN - Number of increments in the Runge-Kutta integration. A value of 10 is normally sufficient.

Y - Final value of charge number.

Of the above variables, the values of the following must be provided by the main program: SCHARG, DCONST, EZERO, V, RSIZE, ECONST, RR, FACTOR, COEFF, AFID, RATE, H, YI, and NN. Y is determined in the subroutine.

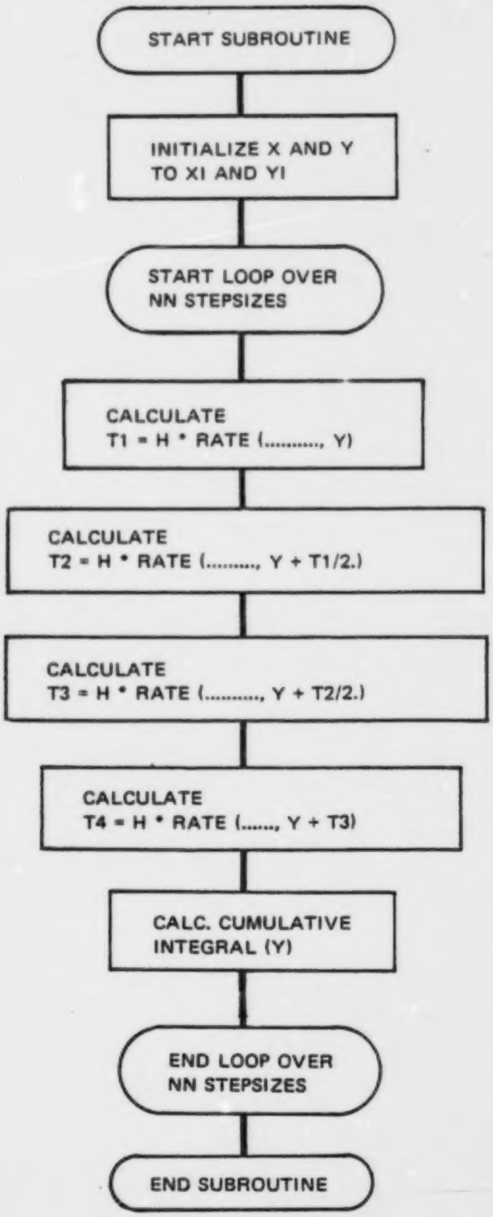

START SUBROUTINE
INITIALIZE X AND Y TO XI AND YI
START LOOP OVER NN STEPSIZES
CALCULATE T1 = H * RATE (.........., Y)
CALCULATE T2 = H * RATE (........., Y + T1/2.)
CALCULATE T3 = H * RATE (.........., Y + T2/2.)
CALCULATE T4 = H * RATE (......, Y + T3)
CALC. CUMULATIVE INTEGRAL (Y)
END LOOP OVER NN STEPSIZES
END SUBROUTINE

Figure 17. Flow chart for subroutine CHARGN.

Statement Function RATE

This statement function calculates the right hand side of equation (12) for use in subroutine CHARGN. In order to use this statement function, subroutines ARCCOS and ZERO must be supplied.

The first and third terms on the right hand side of equation (12) are calculated in a straight forward manner. However, the third term involves an integration over the angle θ which must be performed numerically. The integration is performed by using the Gaussian quadrature[34] which is given by

$$\int_{\theta_o}^{\pi/2} f(\theta)d\theta = \frac{\pi/2 - \theta_o}{2} \int_{-1}^{1} F(t)dt \quad , \qquad (49)$$

where

$$\theta = \tfrac{1}{2}(\pi/2 - \theta_o)t + \tfrac{1}{2}(\theta_o + \pi/2) \quad , \qquad (50)$$

and the integral

$$\int_{-1}^{1} F(t)dt = A_oF(t_o) + A_1F(t_1) + \cdots\cdots A_nF(t_n) \qquad (51)$$

is evaluated using tabulated values of $A_k(k = 0,1 \cdots\cdots n)$ and $t_k(k = 0,1 \cdots\cdots n)$. The subprogram performs the operations indicated in equations (49) and (51) for a fixed number of points, n = 3.

If the charge on the particle is equal to or greater than the saturation charge, the first term on the right hand side of equation (46) is set equal to zero. Once the three terms on the right hand side of equation (46) are calculated, then they are added to give the total charging rate.

Figure 18 shows a detailed flow chart for this subprogram. All information which is transmitted between subroutine CHARGN and this function subprogram is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

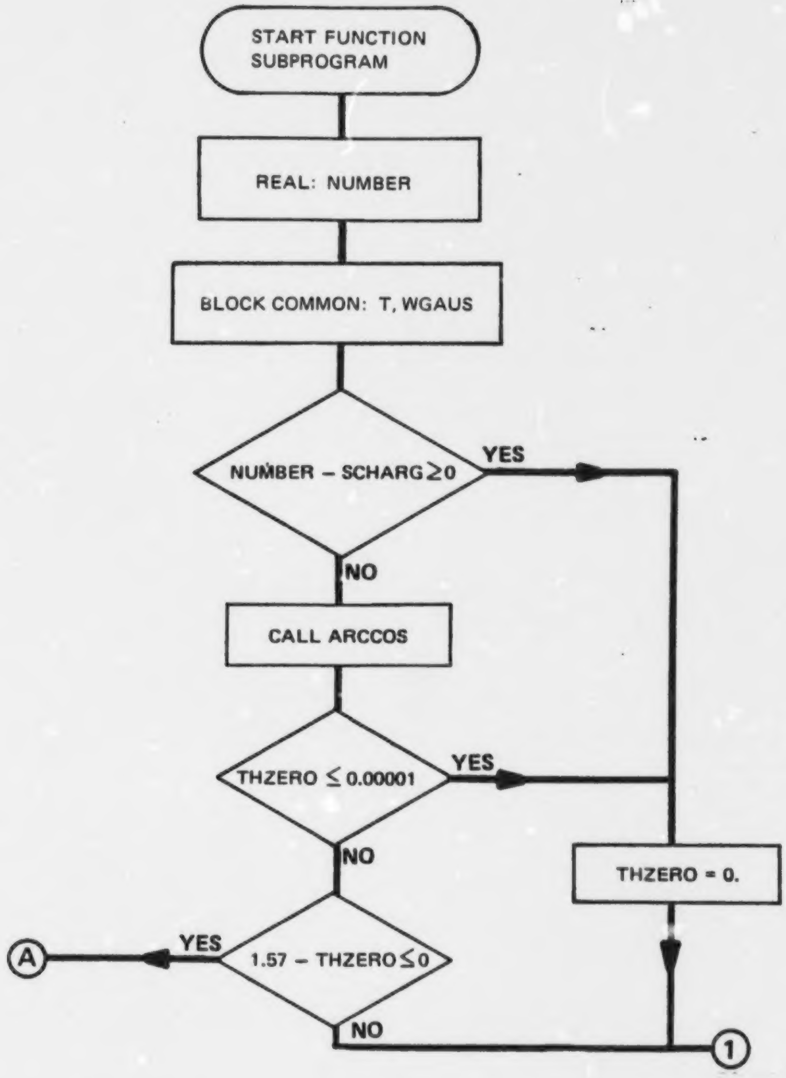

START FUNCTION SUBPROGRAM
REAL: NUMBER
BLOCK COMMON: T, WGAUS
NUMBER – SCHARG ≥ 0
YES
NO
CALL ARCCOS
THZERO ≤ 0.00001
YES
NO
THZERO = 0.
1.57 – THZERO ≤ 0
YES
NO
A
1

Figure 18. Flow chart for function subprogram RATE (Sheet 1 of 3).

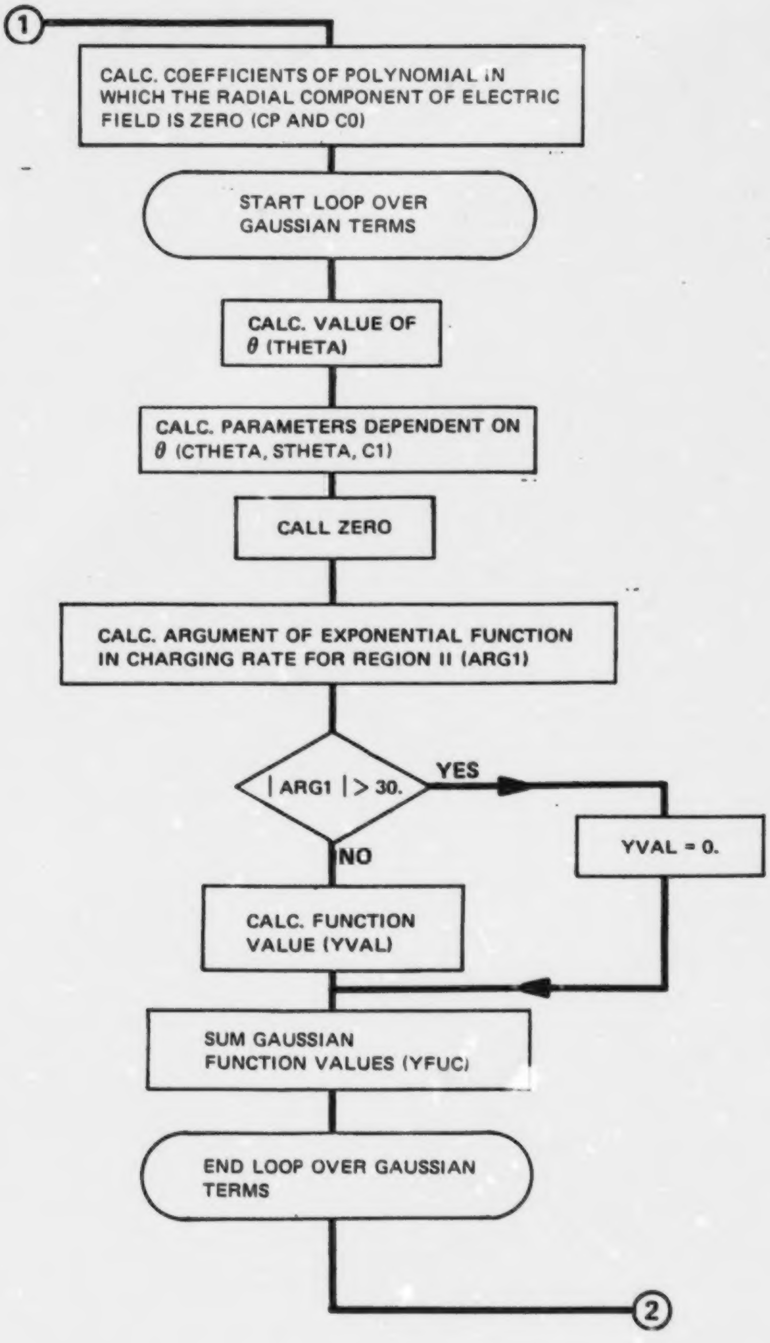
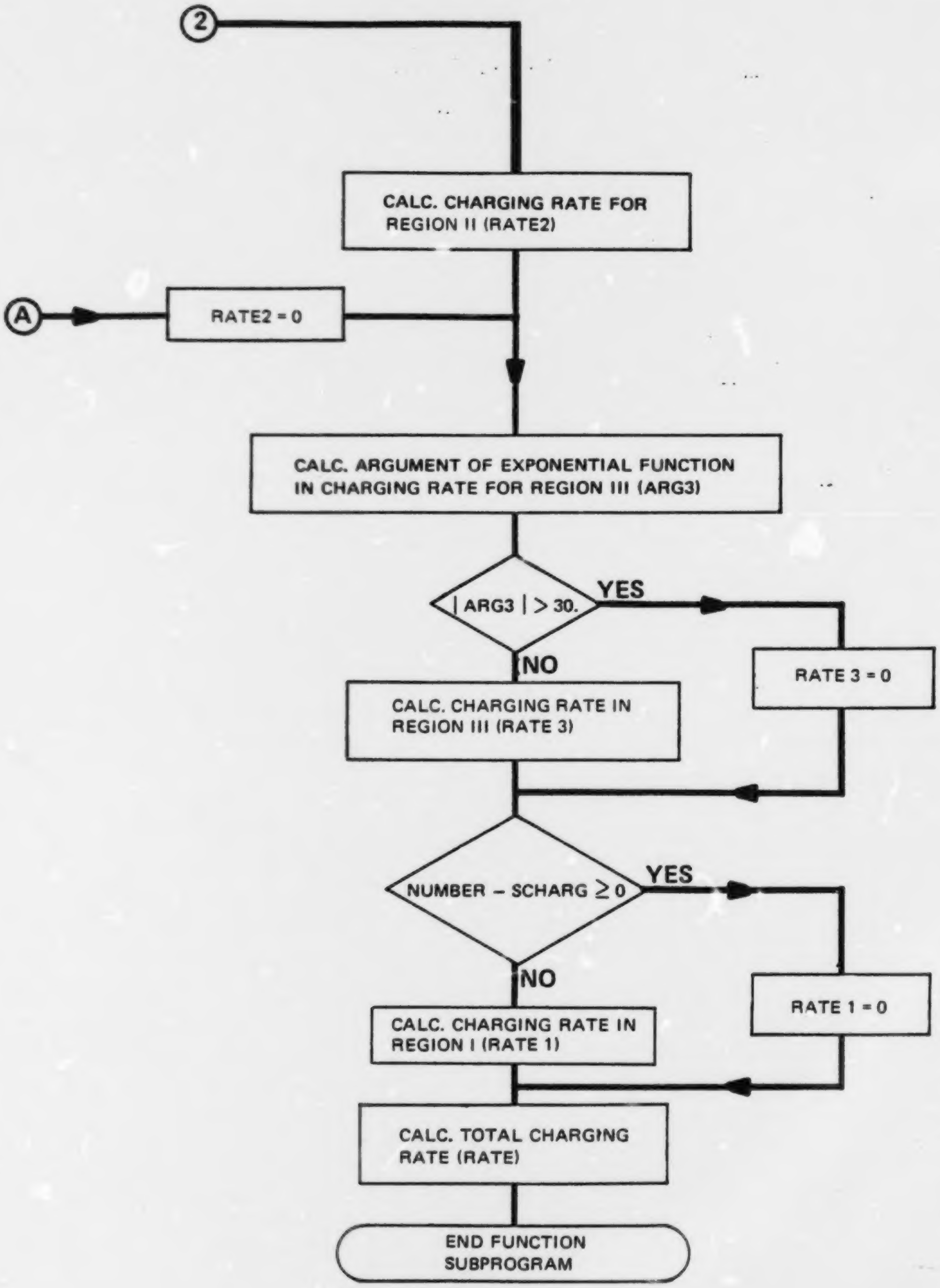

①
CALC. COEFFICIENTS OF POLYNOMIAL IN WHICH THE RADIAL COMPONENT OF ELECTRIC FIELD IS ZERO (CP AND C0)
START LOOP OVER GAUSSIAN TERMS
CALC. VALUE OF θ (THETA)
CALC. PARAMETERS DEPENDENT ON θ (CTHETA, STHETA, C1)
CALL ZERO
CALC. ARGUMENT OF EXPONENTIAL FUNCTION IN CHARGING RATE FOR REGION II (ARG1)
| ARG1 | > 30.
YES
YVAL = 0.
NO
CALC. FUNCTION VALUE (YVAL)
SUM GAUSSIAN FUNCTION VALUES (YFUC)
END LOOP OVER GAUSSIAN TERMS
②

Figure 18. Flow chart for function subprogram RATE (Sheet 2 of 3).



2
CALC. CHARGING RATE FOR REGION II (RATE2)
A
RATE2 = 0
CALC. ARGUMENT OF EXPONENTIAL FUNCTION IN CHARGING RATE FOR REGION III (ARG3)
| ARG3 | > 30.
YES
NO
RATE 3 = 0
CALC. CHARGING RATE IN REGION III (RATE 3)
NUMBER – SCHARG ≥ 0
YES
NO
RATE 1 = 0
CALC. CHARGING RATE IN REGION I (RATE 1)
CALC. TOTAL CHARGING RATE (RATE)
END FUNCTION SUBPROGRAM

Figure 18. Flow chart for function subprogram RATE (Sheet 3 of 3).

SCHARG - Value of saturation charge number from the field charging equation [see eq. (13)].

DCONST - Value of the quantity $[\frac{(K-1)}{(K+2)} a^3]$ found in equation (12) $[m^3]$.

EZERO - Applied electric field strength for particle charging (V/m).

V - Value of the quantity $[\frac{e^2}{4\pi\varepsilon_0 akT}]$ found in equation (12).

RSIZE - Radius of the particle (m).

ECONST - Value of the quantity $[\frac{3eE_0 a}{kT(K+2)}]$ found in equation (12).

RR - Value of the quantity $[\frac{eE_0}{kT}]$ found in equation (12) $[m^{-1}]$.

FACTOR - Value of the quantity $[\frac{\pi \tilde{v} a^2}{2}]$ found in equation (12) $[m^3/sec]$.

COEFF - Value of the quantity $[\frac{bq_s}{4\varepsilon_0}]$ found in equation (12) $[m^3/sec]$.

AFID - Free ion density for particle charging $(\#/m^3)$.

NUMBER - Particle charge number (coul).

Of the above variables, the values of the following must be provided by subroutine CHARGN: SCHARG, DCONST, EZERO, V, RSIZE, ECONST, RR, FACTOR, COEFF, AFID, and NUMBER. The total charging rate given on the right hand side of equation (12) is RATE and is determined in the statement function.

Subroutine ARCCOS

This subroutine calculates the inverse cosine of a number. The calculation is performed by using the series expansion given by[35]

$$\cos^{-1}x = \frac{\pi}{2} - \left(x + \frac{x^3}{2.3} + \frac{1.3}{2.4.5} x^5 + \frac{1.3.5}{2.4.6.7} x^7 + \cdots\right) \quad , \qquad (52)$$

where $x^2<1$ and $0<\cos^{-1}x<\pi$.

The subroutine is specialized in that the number x is determined by the ratio A/B of two numbers. This is done because in the particle charging theory the inverse cosine of the ratio of the particle charge to the saturation charge must be calculated. However, the subroutine can be used in general by setting B=1, so that A becomes the number whose inverse cosine is determined. The series in equation (52) is terminated when a term is reached which is equal to or less than 0.00001.

Figure 19 shows a detailed flow chart for this subroutine. All information which is transmitted between this subroutine and other main or subprograms is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

A - Numerator of the ratio A/B whose inverse cosine is to be determined.

B - Denominator of the ratio A/B whose inverse cosine is to be determined.

RCOS - Value of the $\cos^{-1}$ (A/B) [radians].

The variables A and B must be supplied to the subroutine and RCOS is determined in the subroutine.

Subroutine ZERO

This subroutine determines the radial distance (r_0) from the center of a charged particle and along a given angle θ for which the total electric field is zero. The use of this subroutine requires that subroutine ARCCOS be supplied.

From the particle charging theory,[36] the condition that the total electric field be zero is given by

$$r_0{}^3 - \left(\frac{ne}{4\pi\varepsilon_0 E_0 \cos\theta}\right) r_0 + 2 \left(\frac{K-1}{K+2}\right) a^3 = 0 \quad , \qquad (53)$$

where the symbols are defined the same as for equation (12).

For a given angle θ, this is a cubic equation in r_0 of the form

$$x^3 - c_1 x + 2c_2 = 0 \quad . \qquad (54)$$

This type of cubic equation has roots given by

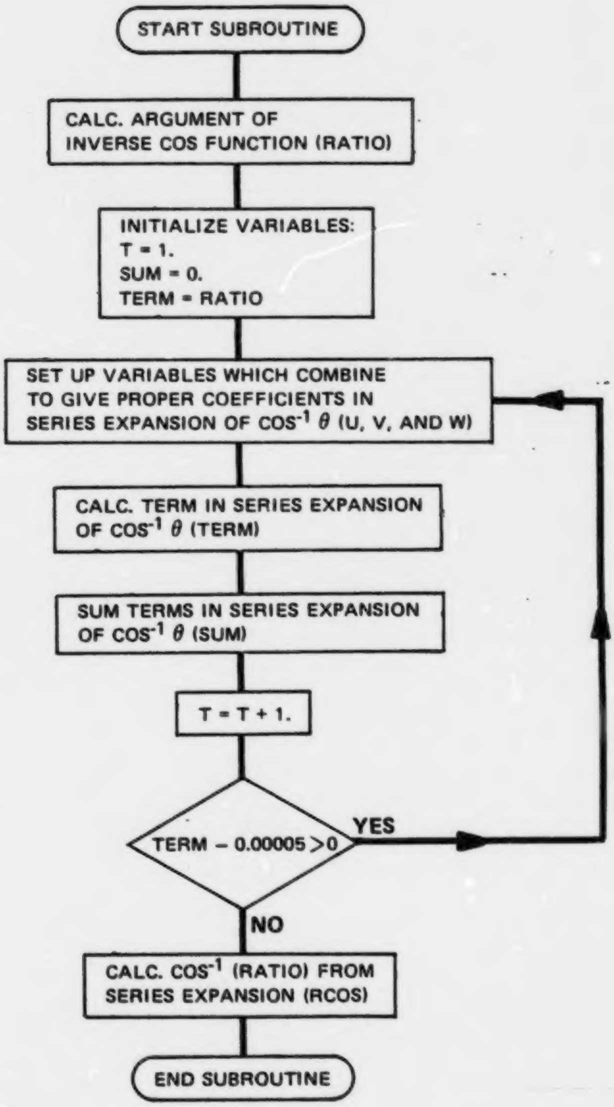

START SUBROUTINE
CALC. ARGUMENT OF INVERSE COS FUNCTION (RATIO)
INITIALIZE VARIABLES:
T = 1.
SUM = 0.
TERM = RATIO
SET UP VARIABLES WHICH COMBINE TO GIVE PROPER COEFFICIENTS IN SERIES EXPANSION OF COS-1 θ (U, V, AND W)
CALC. TERM IN SERIES EXPANSION OF COS-1 θ (TERM)
SUM TERMS IN SERIES EXPANSION OF COS-1 θ (SUM)
T = T + 1.
TERM – 0.00005 > 0
YES
NO
CALC. COS-1 (RATIO) FROM SERIES EXPANSION (RCOS)
END SUBROUTINE

Figure 19. Flow chart for subroutine ARCCOS.

$$x = -2\sqrt{\frac{c_1}{3}} \cos\left\{ \frac{\cos^{-1}\sqrt{\frac{27c_2^2}{c_1^3}}}{3} + \frac{2\pi}{3}\, n \right\} \qquad (55)$$

where n = 0,1,2. For particle charging, the physically meaningful solution is given for n=1

$$r_0 = -2\sqrt{\frac{ne}{12\pi\varepsilon_0 E_0 \cos\theta}} \cdot$$

$$\cos\left\{ \frac{\cos^{-1}\sqrt{27\left(\frac{K-1}{K+2}\right)^2 \left(\frac{4\pi\varepsilon_0 a^2 E_0 \cos\theta}{ne}\right)^3}}{3} + \frac{2\pi}{3} \right\} . \qquad (56)$$

The subroutine determines r_0 from equation (56).

Figure 20 shows a detailed flow chart for this subroutine. This subroutine is called by statement function RATE and all information which is transmitted between these subprograms is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

C1 - Value of the coefficient $[\frac{q}{4\pi\varepsilon_0 E_0 \cos\theta}]$ of r_0 in equation (52) [m].

C0 - Value of one-half the constant term $[(\frac{K-1}{K+2})\, a^3]$ in equation (52) [m^4/V].

RZERO - Radial distance from the center of a charged particle and along a given angle θ for which the total electric field is zero.

The variables C1 and C0 are supplied by statement function RATE and RZERO is determined in the subroutine.

Subroutine CHGSUM

This subroutine calculates particle charge as a function of residence time, electrical conditions, gas conditions, and particle characteristics by using equation (15). Although the subroutine utilizes equation (15) in a straightforward manner, the programming is involved in that the values of charge at the end of each length increment due to field and diffusion charging must be kept track of independent of one another and the charging process must be

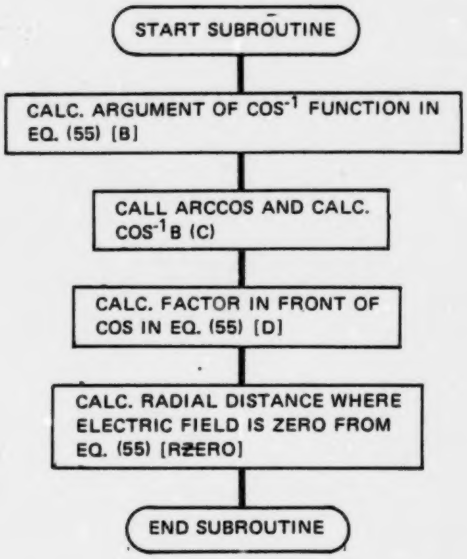

START SUBROUTINE
CALC. ARGUMENT OF COS-1 FUNCTION IN EQ. (55) [B]
CALL ARCCOS AND CALC. COS-1 B (C)
CALC. FACTOR IN FRONT OF COS IN EQ. (55) [D]
CALC. RADIAL DISTANCE WHERE ELECTRIC FIELD IS ZERO FROM EQ. (55) [RZERO]
END SUBROUTINE

Figure 20. Flow chart for subroutine ZERO.

incorporated into the incremental or incremental plus subincremental schemes that may be utilized in the main program. Since the free ion density and electric field change along the length of a precipitator, the values of charge due to field and diffusion charging must be saved at the end of each increment or subincrement so that they can be used as initial values for the next increment or subincrement. Also, provisions must be made to ensure that the charge acquired due to the field charging term in equation (15) does not exceed the saturation charge in any given increment or subincrement.

Figure 21 shows a detailed flow chart for this subroutine. This subroutine is called by the main program and all information which is transmitted between the main program and this subroutine is transferred through block common statements. The following is a list with descriptions of those variables which must be transmitted between the main program and this subroutine:

TDK - Temperature of the gas stream (°K).

U - Gas ion mobility (m^2/V-sec).

E - Electronic charge unit (coul).

EPSO - Permittivity of free space (coul/V•m).

BC - Boltzmann's constant (J/°K).

VAVC - Mean thermal speed of gas ions (m/sec).

NVI - Indicator which can have the values of 1 and 2. If NVI = 1, then known or measured operating voltages and currents are used in the main program and only incremental lengths are taken. If NVI = 2, then the operating voltages and currents are calculated in the main program and incremental plus subincremental lengths are taken.

I - Index which runs over incremental lengths.

SCHARG - Saturation number from field charging theory.

CHRFID - Average free ion density (#/m^3).

TIMEI - Time at the start of a given incremental or subincremental length (sec).

TIMEF - Time at the end of a given incremental or subincremental length (sec).

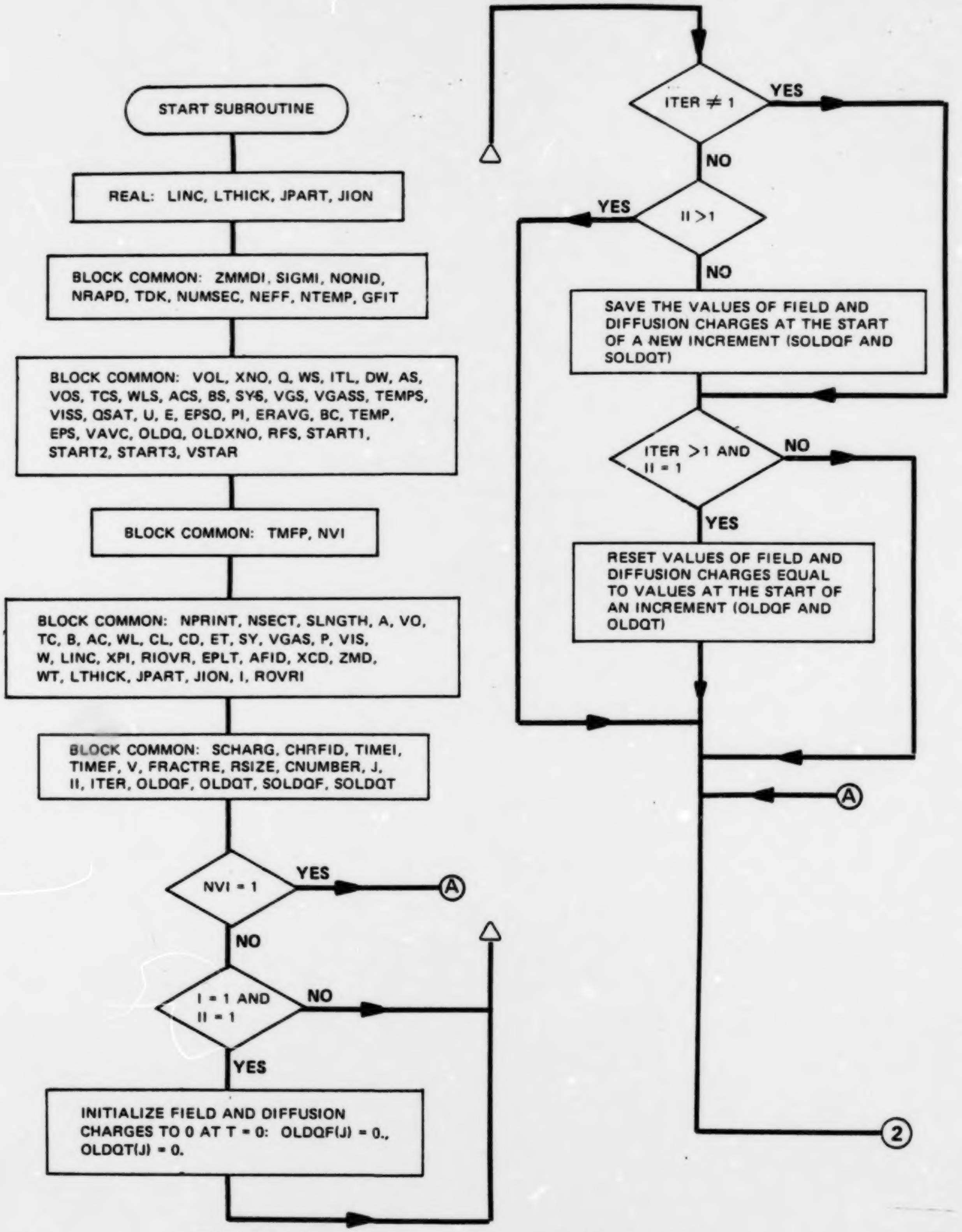

START SUBROUTINE
REAL: LINC, LTHICK, JPART, JION
BLOCK COMMON: ZMMDI, SIGMI, NONID, NRAPD, TDK, NUMSEC, NEFF, NTEMP, GFIT
BLOCK COMMON: VOL, XNO, Q, WS, ITL, DW, AS, VOS, TCS, WLS, ACS, BS, SY6, VGS, VGASS, TEMPS, VISS, QSAT, U, E, EPSO, PI, ERAVG, BC, TEMP, EPS, VAVC, OLDQ, OLDXNO, RFS, START1, START2, START3, VSTAR
BLOCK COMMON: TMFP, NVI
BLOCK COMMON: NPRINT, NSECT, SLNGTH, A, VO, TC, B, AC, WL, CL, CD, ET, SY, VGAS, P, VIS, W, LINC, XPI, RIOVR, EPLT, AFID, XCD, ZMD, WT, LTHICK, JPART, JION, I, ROVRI
BLOCK COMMON: SCHARG, CHRFID, TIMEI, TIMEF, V, FRACTRE, RSIZE, CNUMBER, J, II, ITER, OLDQF, OLDQT, SOLDQF, SOLDQT
NVI = 1
YES
Ⓐ
NO
I = 1 AND II = 1
NO
YES
INITIALIZE FIELD AND DIFFUSION CHARGES TO 0 AT T = 0: OLDQF(J) = 0., OLDQT(J) = 0.
ITER ≠ 1
YES
NO
II > 1
YES
NO
SAVE THE VALUES OF FIELD AND DIFFUSION CHARGES AT THE START OF A NEW INCREMENT (SOLDQF AND SOLDQT)
ITER > 1 AND II = 1
NO
YES
RESET VALUES OF FIELD AND DIFFUSION CHARGES EQUAL TO VALUES AT THE START OF AN INCREMENT (OLDQF AND OLDQT)
Ⓐ
②

Figure 21. Flow chart for subroutine CHGSUM (Sheet 1 of 3).

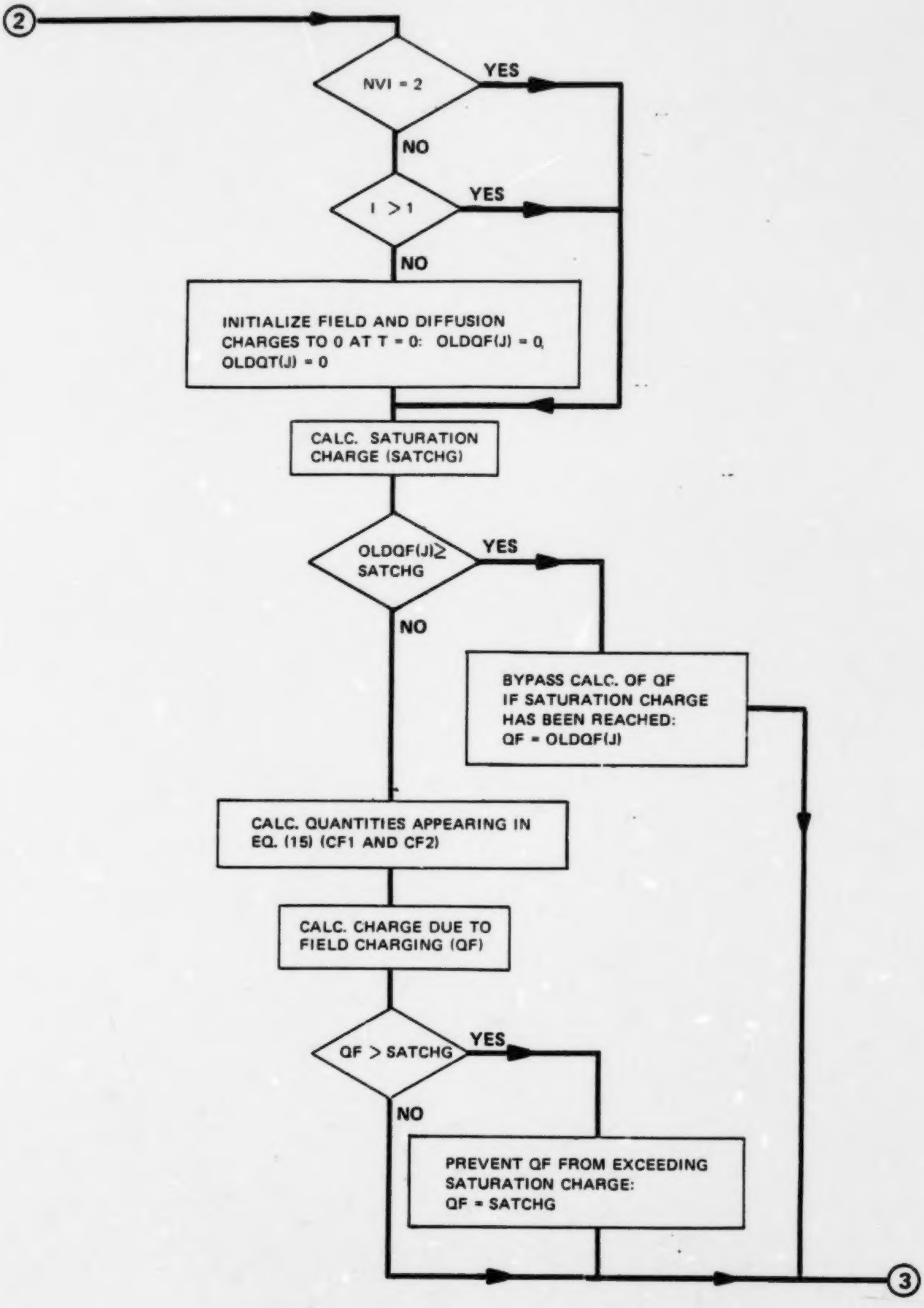

②
NVI = 2
YES
NO
I > 1
YES
NO
INITIALIZE FIELD AND DIFFUSION CHARGES TO 0 AT T = 0: OLDQF(J) = 0, OLDQT(J) = 0
CALC. SATURATION CHARGE (SATCHG)
OLDQF(J) ≥ SATCHG
YES
NO
BYPASS CALC. OF QF IF SATURATION CHARGE HAS BEEN REACHED: QF = OLDQF(J)
CALC. QUANTITIES APPEARING IN EQ. (15) (CF1 AND CF2)
CALC. CHARGE DUE TO FIELD CHARGING (QF)
QF > SATCHG
YES
NO
PREVENT QF FROM EXCEEDING SATURATION CHARGE: QF = SATCHG
③

Figure 21. Flow chart for subroutine CHGSUM (Sheet 2 of 3).

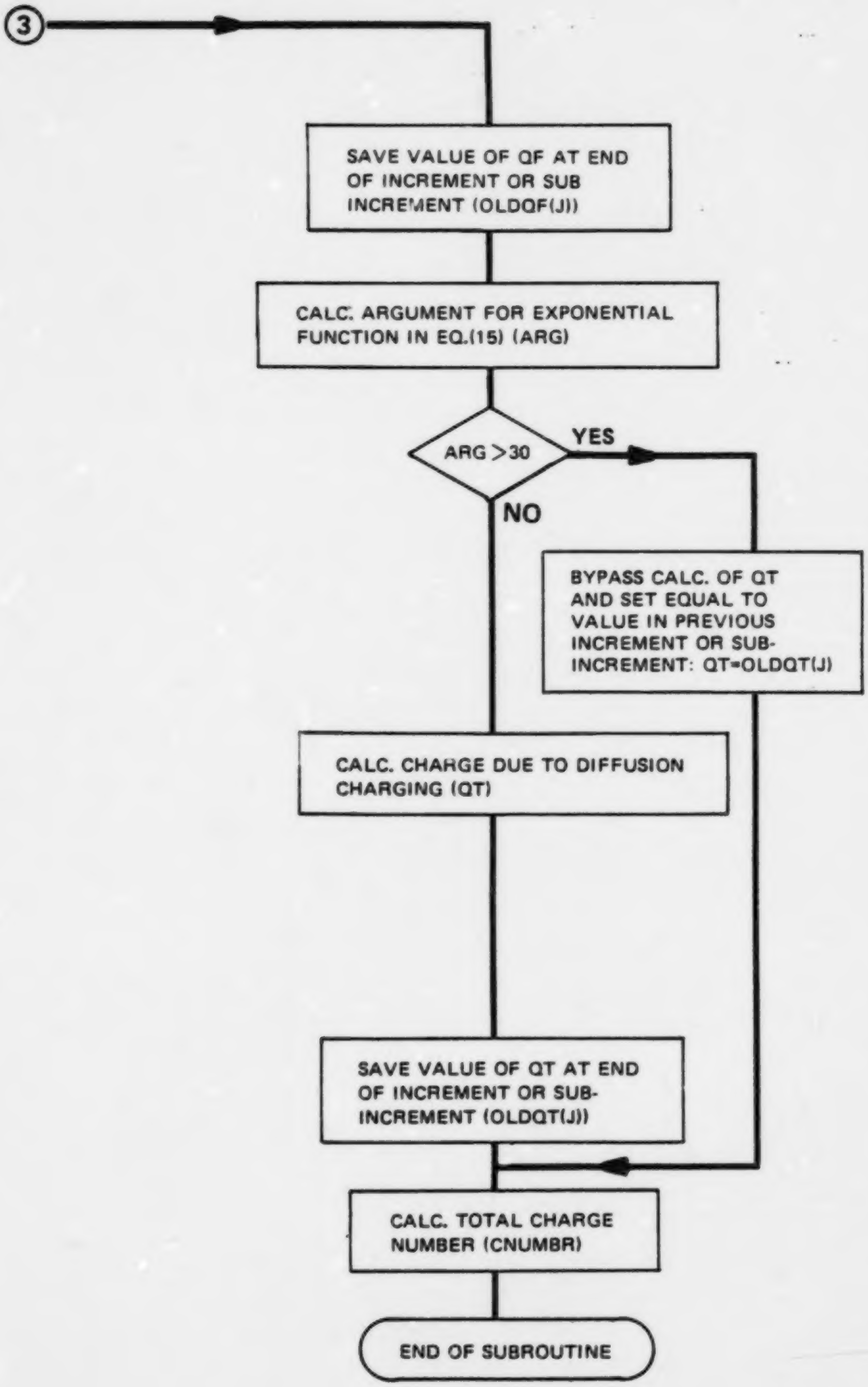

③
SAVE VALUE OF QF AT END OF INCREMENT OR SUB INCREMENT (OLDQF(J))
CALC. ARGUMENT FOR EXPONENTIAL FUNCTION IN EQ.(15) (ARG)
ARG > 30
YES
NO
BYPASS CALC. OF QT AND SET EQUAL TO VALUE IN PREVIOUS INCREMENT OR SUB-INCREMENT: QT=OLDQT(J)
CALC. CHARGE DUE TO DIFFUSION CHARGING (QT)
SAVE VALUE OF QT AT END OF INCREMENT OR SUB-INCREMENT (OLDQT(J))
CALC. TOTAL CHARGE NUMBER (CNUMBR)
END OF SUBROUTINE

Figure 21. Flow chart for subroutine CHGSUM (Sheet 3 of 3).

V - Value of the quantity $[\frac{e^2}{4\pi\varepsilon_0 akT}]$.

RSIZE - Radius of a given particle size (m).

CNUMBR - Total charge number due to the sum of field and diffusional charges.

J - Index which runs over particle sizes.

II - Index which runs over subincremental lengths.

ITER - Counter that indicates which iteration is being performed over subincremental lengths in a given increment (necessary when NVI = 2).

OLDQF(J) - Value of field charge at the end of a given increment or subincrement (coul).

OLDQT(J) - Value of diffusion charge at the end of a given increment or subincrement (coul).

SOLDQF(J) - Value of field charge at the start of an increment which must be saved when NVI = 2 for the iteration procedure over subincrements in a given increment (coul).

SOLDQT(J) - Value of diffusion charge at the start of an increment which must be saved when NVI = 2 for the iteration procedure over subincrements in a given increment (coul).

Of the above variables, the values of the following must be provided by the main program: TDK, U, E, EPSO, BC, VAVC, NVI, I, SCHARG, CHRFID, TIMEI, TIMEF, V, RSIZE, J, II, and ITER. The values of the following variables are determined in the subroutine: CNUMBR, OLDQF, OLDQT, SOLDQF, and SOLDQT. In the above arrays, I, J, and II can not exceed values of 45, 20, and 30, respectively. The restrictions on I, J, and II limit the number of length increments, the number of particle size bands, and the number of subincremental lengths in a given length increment, respectively.

Subroutine ADJUST

This subroutine performs the following operations: (1) it takes the unadjusted, ideally-calculated migration velocities and adjusts them in order to account for unmodeled and nonideal effects; (2) it determines the discrete outlet mass loadings, $\Delta M/\Delta\log_{10}D$, for each particle size band for no-rap and no-rap + rap conditions and for the rapping puff; (3) it prints out opacity data based on those mass loadings; (4) it prints out detailed information of interest concerning precipitator operating conditions and performance; and (5) it prints out a table which summarizes precipitator operating conditions and performance. In order to use this subroutine, subroutines WADJST, LNDIST, LNFIT, PRTSUM, OPAC, MASARA, ARAOPT, and MIE must be supplied.

The first calculation of significance which is performed is the determination of the unadjusted, ideal overall mass collection fraction (X). This quantity is determined by using the expression

$$X = \sum_i \left[(DXS)_i / (ONO)_i \right] \cdot (PCNT)_i$$

$$= \sum_i (EFESR)_i \cdot (PCNT)_i \quad , \qquad (57)$$

where $(DXS)_i$ = the number of particles per cubic meter of gas in the i-th size band collected over the entire length of the precipitator under unadjusted, ideal conditions ($\#/m^3$),

$(ONO)_i$ = the number of particles per cubic meter of gas in the i-th size band in the inlet size distribution ($\#/m^3$),

$(PCNT)_i$ = the fraction by mass of the i-th particle size band in the inlet size distribution, and

$(EFESR)_i$ = the unadjusted, ideal collection fraction for the i-th particle size band over the entire length of the precipitator.

The rest of the subroutine is structured around two major loops. The outside loop runs over different "rapping puff" size distributions. The variable NRAPDC is a counter for this loop and it runs over a number of different "rapping puff" size distributions which is equal to the specified value of the variable NRAPD. The inside loop runs over different sets of nonideal conditions of gas velocity nonuniformity, gas sneakage, and particle reentrainment without rapping. The variable NONCK is a counter for this loop and it runs over a number of sets of nonideal conditions which is equal to the specified value of the variable NONID.

The initial rapping puff size distribution is fixed to be a log-normal distribution with a MMD = 6.0 μm and a $\sigma_p = 2.5$. These values correspond to the field data discussed previously and were obtained from Figure 6. Other distributions can be analyzed in the procedure discussed previously by specifying different sets of values of the MMD and σ_p in the input data to the main program. For each specified set of MMD and σ_p, the subroutine constructs a log-normal size distribution by calling subroutine LNDIST. The percentage by mass of each particle size band in the rapping puff is stored in the array RPCNT(I).

After the rapping puff size distribution is established in the outer loop, the nonideal conditions of gas velocity nonuniformity, gas sneakage, and particle reentrainment without rapping are established in the inner loop. At this point corrections are made to the unadjusted, ideal migration velocity for each particle size band in order to account for unmodeled and nonideal effects. The unadjusted, ideal migration velocity (WY) for each size band is calculated from the expression

$$WY = (VG/ATOTAL) \cdot 100 \cdot \ln\,(100/(100-XEP)) \quad , \qquad (58)$$

where VG = total gas volume flow rate (m^3/sec),

ATOTAL = total collection plate area (m^2), and

XEP = 100·EFESR (%).

However, if EFESR $\geq$ 0.99999, WY is set equal to the value of the unadjusted, ideal migration velocity in the last increment of the precipitator.

The ideal effective migration velocities are corrected first for gas velocity nonuniformity using equation (17) and then for gas sneakage and/or particle reentrainment without rapping using equation (19). The resulting migration velocities are representative of unadjusted no-rap conditions. These unadjusted no-rap migration velocities are then corrected for unmodeled effects by using subroutine WADJST which applies the size-dependent correction factor shown in Figure 7 to each particle size band. The resulting migration velocities (WY) will be referred to as the no-rap migration velocities. No-rap collection fractions (EFESR) are determined from the no-rap migration velocities using equation (2). Again, if EFESR $\geq$ 0.99999, then WY is set equal to the value of the unadjusted, ideal migration velocity in the last increment of the precipitator. The no-rap collection fractions for the different size bands are used to calculate a no-rap overall mass collection fraction using the same format as in equation (57). No-rap penetrations are also calculated.

The next set of calculations which are performed reduces the no-rap migration velocities in order to account for the effects of rapping reentrainment by using the procedure discussed previously. The total mass which is reentrained due to rapping is determined by using either equation (24) or (25). The mass collected in the last section is calculated using the no-rap overall mass collection efficiency and equation (22). The total mass which is reentrained due to rapping and the rapping puff size distribution are used to determine the number of particles in each size band which is reentrained. The number of particles reentrained is subtracted from the total number of particles collected under no-rap conditions to give the number of particles collected under no-rap + rap conditions. If the number of particles collected under no-rap + rap conditions is calculated to be a negative number, the number collected under no-rap conditions is used in its place. The number of particles in each size band collected under no-rap + rap conditions and the number of particles in each size band in the inlet size distribution are used to calculate no-rap + rap collection efficiencies, penetrations, migration velocities, and overall mass collection efficiency.

Next, several calculations are made to describe the outlet emissions under no-rap and no-rap + rap conditions and for the rapping puff. In each case, the size band penetrations are normalized and the outlet size distribution is obtained. These size distributions are then fitted to a log-normal distribution by calling subroutine LNFIT. Also, in each case, the discrete outlet mass loadings are determined by calculating $\Delta M/\Delta \log_{10} D$ for each size band.

The results of the calculations discussed above are printed out in three different sections: (1) Particle Size Range Statistics; (2) Unadjusted Migration Velocities and Efficiencies, and Discrete Outlet Mass Loadings; and (3) Summary Table of ESP Operating Parameters and Performance. The third section of printout is obtained by calling subroutine PRTSUM. If effluent opacity data is required, the necessary data is calculated and printed by a call to subroutine OPAC. This takes place immediately preceding the call to subroutine PRTSUM so that opacity data may be entered in the Summary Table. The output data from the program is discussed in detail in Volume II and will not be discussed further here.

Figure 22 shows a detailed flow chart for this subroutine. This subroutine is called by the main program and all information which is transmitted between the main program, subroutine PRTSUM, and this subroutine is transferred through block common statements. The following is a list with descriptions of those variables which must be transmitted between the main program and this subroutine.

DIAM(I) - Midpoint of a given particle size band (m).

ONO(I) - Number of particles per unit volume of gas for a given particle size band entering the precipitator ($\#/m^3$).

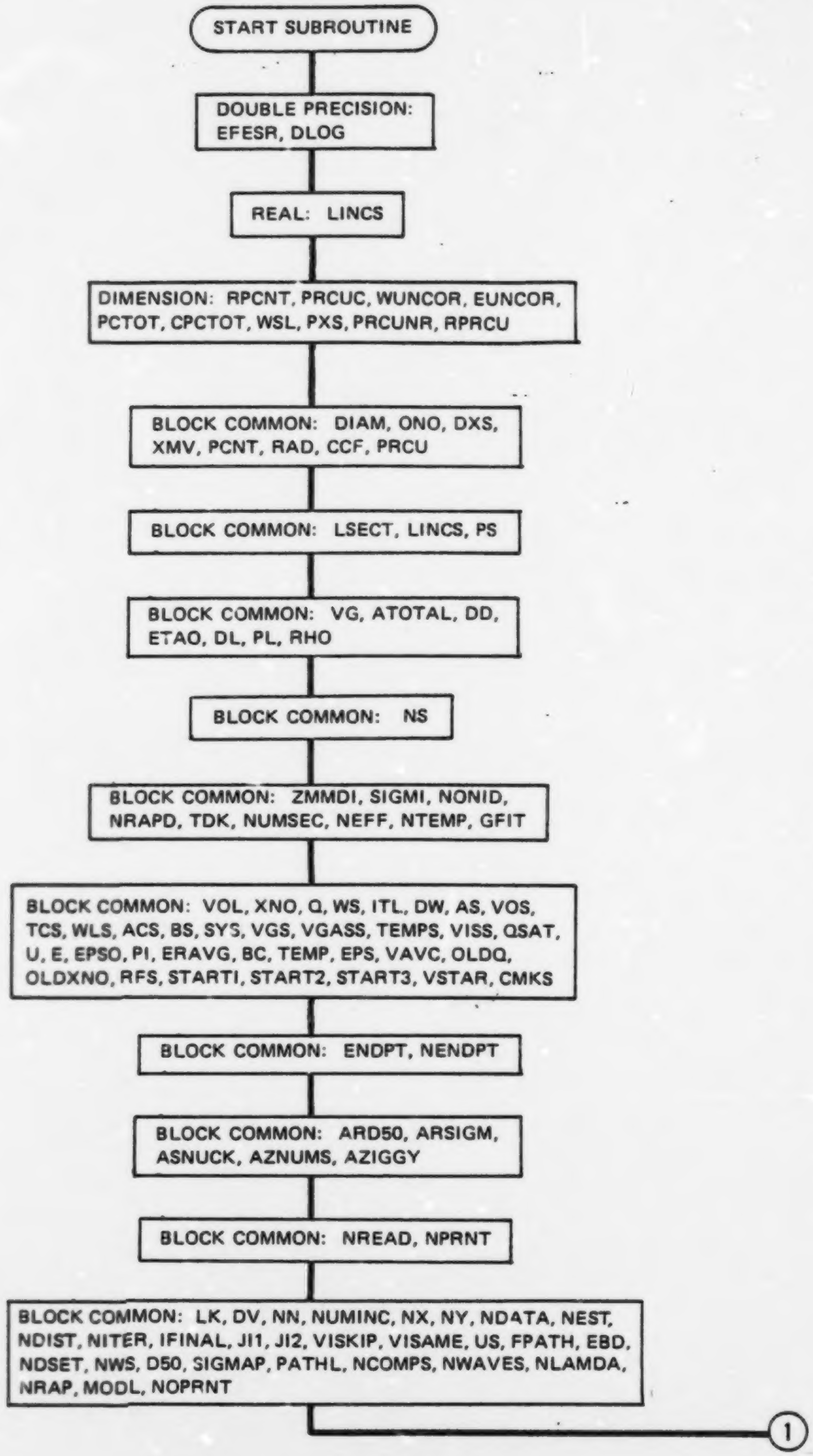

START SUBROUTINE
DOUBLE PRECISION: EFESR, DLOG
REAL: LINCS
DIMENSION: RPCNT, PRCUC, WUNCOR, EUNCOR, PCTOT, CPCTOT, WSL, PXS, PRCUNR, RPRCU
BLOCK COMMON: DIAM, ONO, DXS, XMV, PCNT, RAD, CCF, PRCU
BLOCK COMMON: LSECT, LINCS, PS
BLOCK COMMON: VG, ATOTAL, DD, ETAO, DL, PL, RHO
BLOCK COMMON: NS
BLOCK COMMON: ZMMDI, SIGMI, NONID, NRAPD, TDK, NUMSEC, NEFF, NTEMP, GFIT
BLOCK COMMON: VOL, XNO, Q, WS, ITL, DW, AS, VOS, TCS, WLS, ACS, BS, SYS, VGS, VGASS, TEMPS, VISS, QSAT, U, E, EPSO, PI, ERAVG, BC, TEMP, EPS, VAVC, OLDQ, OLDXNO, RFS, START1, START2, START3, VSTAR, CMKS
BLOCK COMMON: ENDPT, NENDPT
BLOCK COMMON: ARD50, ARSIGM, ASNUCK, AZNUMS, AZIGGY
BLOCK COMMON: NREAD, NPRNT
BLOCK COMMON: LK, DV, NN, NUMINC, NX, NY, NDATA, NEST, NDIST, NITER, IFINAL, JI1, JI2, VISKIP, VISAME, US, FPATH, EBD, NDSET, NWS, D50, SIGMAP, PATHL, NCOMPS, NWAVES, NLAMDA, NRAP, MODL, NOPRNT
①

Figure 22. Flow chart for subroutine ADJUST (Sheet 1 of 13).

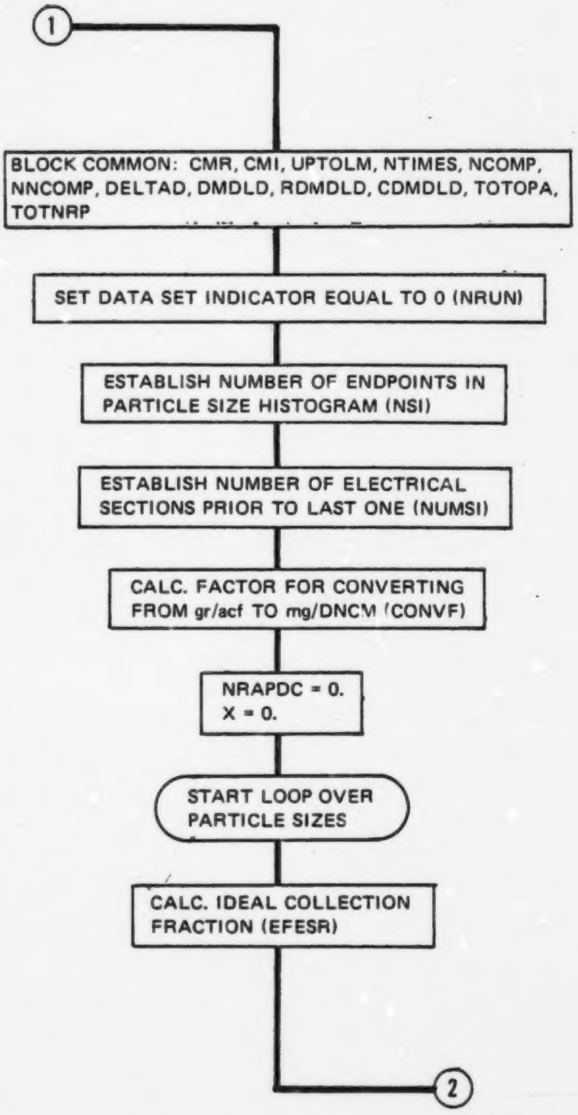

①
BLOCK COMMON: CMR, CMI, UPTOLM, NTIMES, NCOMP, NNCOMP, DELTAD, DMDLD, RDMDLD, CDMDLD, TOTOPA, TOTNRP
SET DATA SET INDICATOR EQUAL TO 0 (NRUN)
ESTABLISH NUMBER OF ENDPOINTS IN PARTICLE SIZE HISTOGRAM (NSI)
ESTABLISH NUMBER OF ELECTRICAL SECTIONS PRIOR TO LAST ONE (NUMSI)
CALC. FACTOR FOR CONVERTING FROM gr/acf TO mg/DNCM (CONVF)
NRAPDC = 0.
X = 0.
START LOOP OVER PARTICLE SIZES
CALC. IDEAL COLLECTION FRACTION (EFESR)
②

Figure 22. Flow chart for subroutine ADJUST (Sheet 2 of 13).

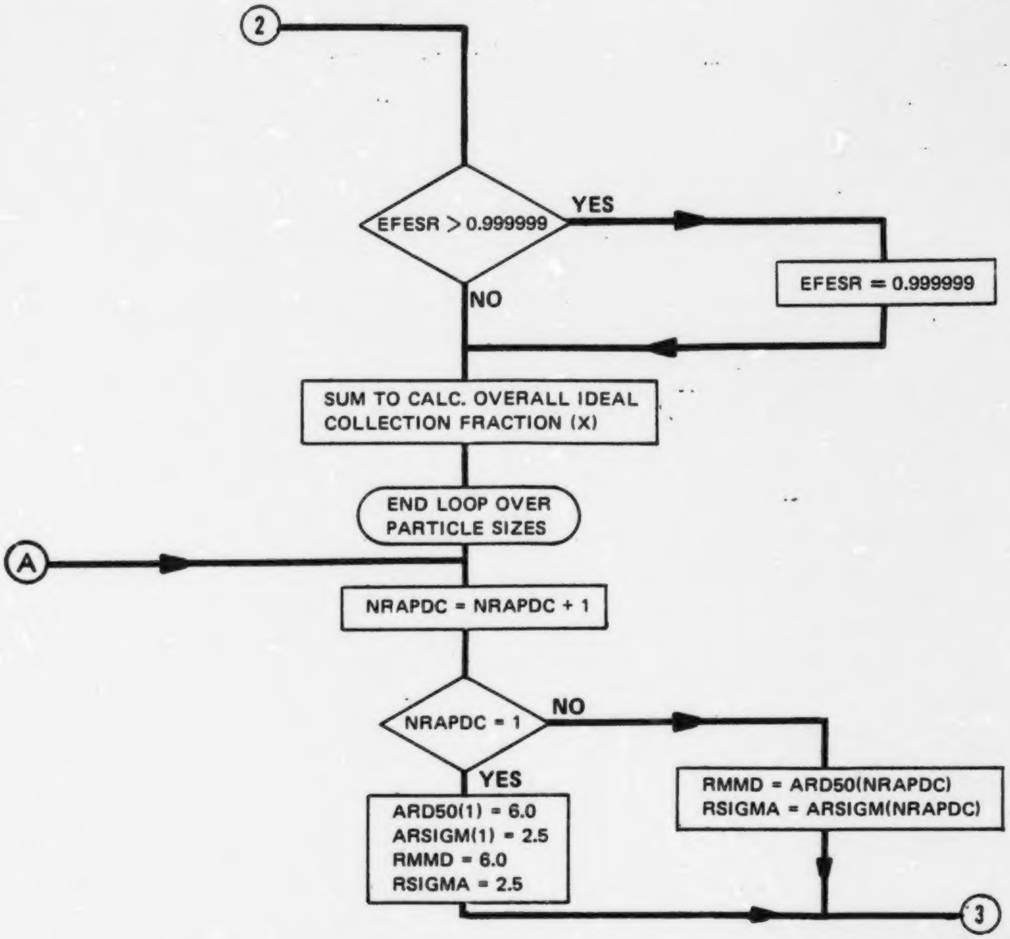

2
EFESR > 0.999999
YES
NO
EFESR = 0.999999
SUM TO CALC. OVERALL IDEAL COLLECTION FRACTION (X)
END LOOP OVER PARTICLE SIZES
A
NRAPDC = NRAPDC + 1
NRAPDC = 1
NO
YES
ARD50(1) = 6.0
ARSIGM(1) = 2.5
RMMD = 6.0
RSIGMA = 2.5
RMMD = ARD50(NRAPDC)
RSIGMA = ARSIGM(NRAPDC)
3

Figure 22. Flow chart for subroutine ADJUST (Sheet 3 of 13).

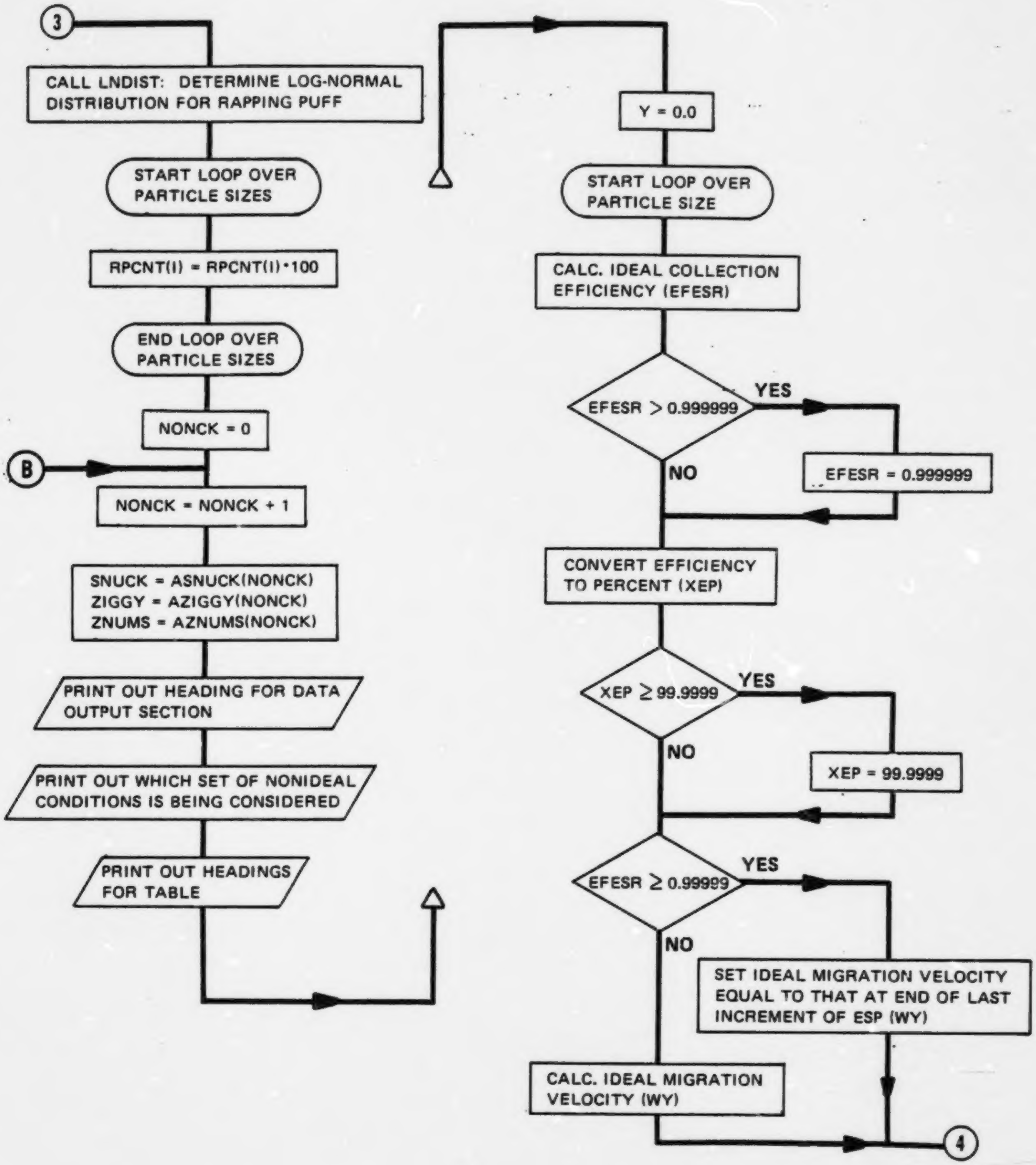

3
CALL LNDIST: DETERMINE LOG-NORMAL DISTRIBUTION FOR RAPPING PUFF
START LOOP OVER PARTICLE SIZES
RPCNT(I) = RPCNT(I)*100
END LOOP OVER PARTICLE SIZES
NONCK = 0
B
NONCK = NONCK + 1
SNUCK = ASNUCK(NONCK)
ZIGGY = AZIGGY(NONCK)
ZNUMS = AZNUMS(NONCK)
PRINT OUT HEADING FOR DATA OUTPUT SECTION
PRINT OUT WHICH SET OF NONIDEAL CONDITIONS IS BEING CONSIDERED
PRINT OUT HEADINGS FOR TABLE
Y = 0.0
START LOOP OVER PARTICLE SIZE
CALC. IDEAL COLLECTION EFFICIENCY (EFESR)
EFESR > 0.999999
YES
NO
EFESR = 0.999999
CONVERT EFFICIENCY TO PERCENT (XEP)
XEP ≥ 99.9999
YES
NO
XEP = 99.9999
EFESR ≥ 0.99999
YES
NO
SET IDEAL MIGRATION VELOCITY EQUAL TO THAT AT END OF LAST INCREMENT OF ESP (WY)
CALC. IDEAL MIGRATION VELOCITY (WY)
4

Figure 22. Flow chart for subroutine ADJUST (Sheet 4 of 13).

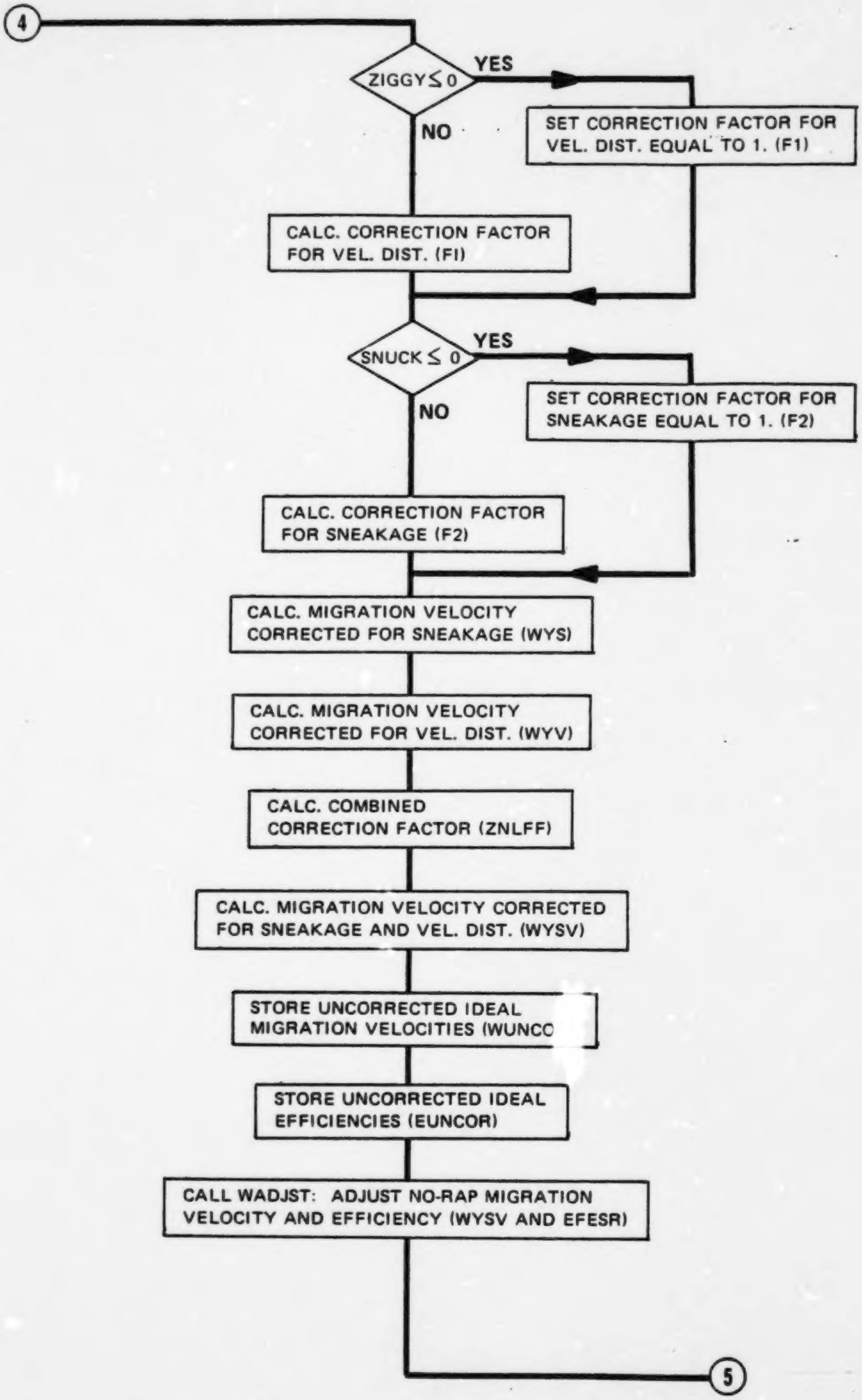

4
ZIGGY ≤ 0
YES
NO
SET CORRECTION FACTOR FOR VEL. DIST. EQUAL TO 1. (F1)
CALC. CORRECTION FACTOR FOR VEL. DIST. (FI)
SNUCK ≤ 0
YES
NO
SET CORRECTION FACTOR FOR SNEAKAGE EQUAL TO 1. (F2)
CALC. CORRECTION FACTOR FOR SNEAKAGE (F2)
CALC. MIGRATION VELOCITY CORRECTED FOR SNEAKAGE (WYS)
CALC. MIGRATION VELOCITY CORRECTED FOR VEL. DIST. (WYV)
CALC. COMBINED CORRECTION FACTOR (ZNLFF)
CALC. MIGRATION VELOCITY CORRECTED FOR SNEAKAGE AND VEL. DIST. (WYSV)
STORE UNCORRECTED IDEAL MIGRATION VELOCITIES (WUNCO
STORE UNCORRECTED IDEAL EFFICIENCIES (EUNCOR)
CALL WADJST: ADJUST NO-RAP MIGRATION VELOCITY AND EFFICIENCY (WYSV AND EFESR)
5

Figure 22. Flow chart for subroutine ADJUST (Sheet 5 of 13).

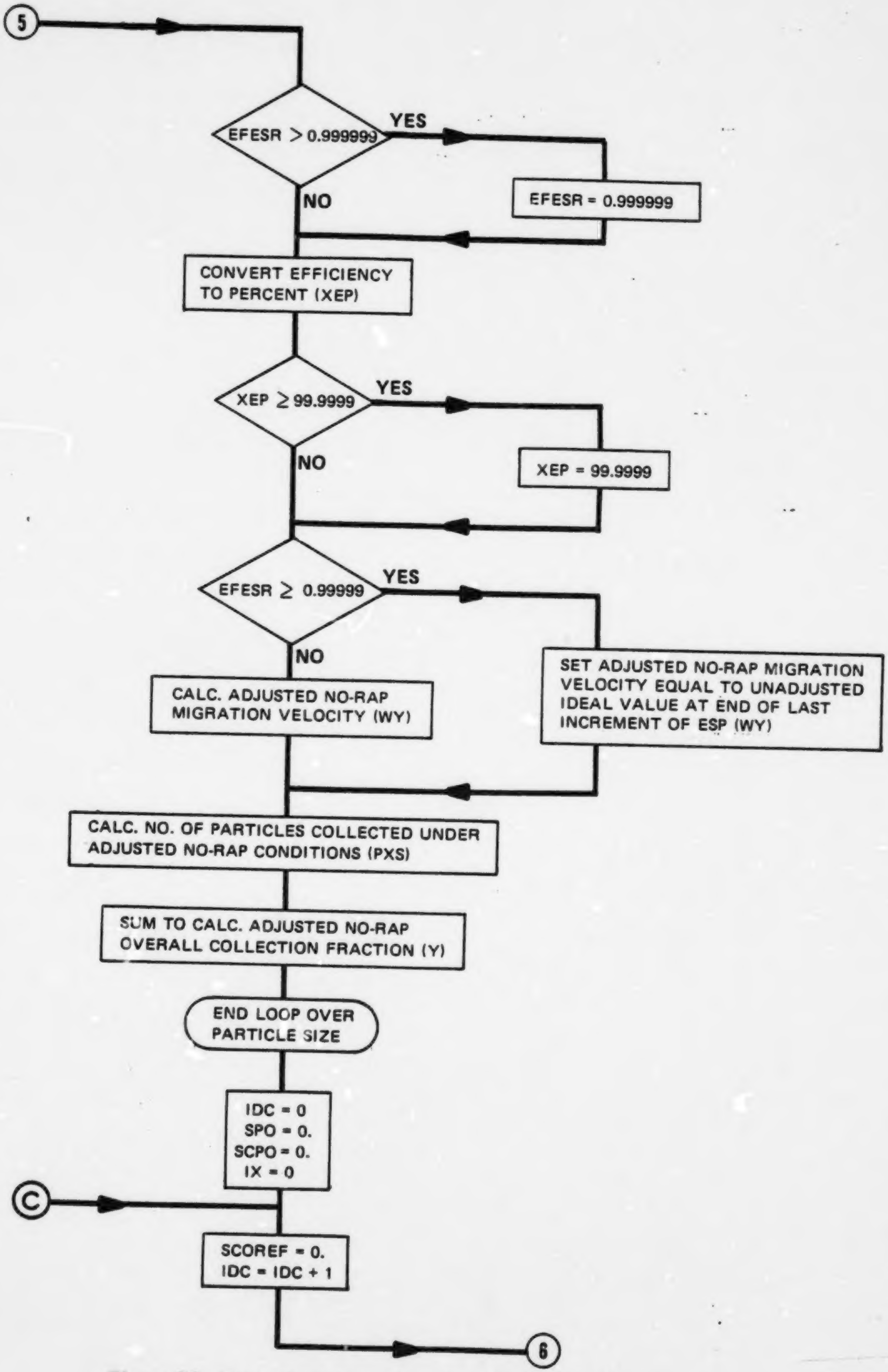

5
EFESR > 0.999999
YES
EFESR = 0.999999
NO
CONVERT EFFICIENCY TO PERCENT (XEP)
XEP ≥ 99.9999
YES
XEP = 99.9999
NO
EFESR ≥ 0.99999
YES
SET ADJUSTED NO-RAP MIGRATION VELOCITY EQUAL TO UNADJUSTED IDEAL VALUE AT END OF LAST INCREMENT OF ESP (WY)
NO
CALC. ADJUSTED NO-RAP MIGRATION VELOCITY (WY)
CALC. NO. OF PARTICLES COLLECTED UNDER ADJUSTED NO-RAP CONDITIONS (PXS)
SUM TO CALC. ADJUSTED NO-RAP OVERALL COLLECTION FRACTION (Y)
END LOOP OVER PARTICLE SIZE
IDC = 0
SPO = 0.
SCPO = 0.
IX = 0
C
SCOREF = 0.
IDC = IDC + 1
6

Figure 22. Flow chart for subroutine ADJUST (Sheet 6 of 13).

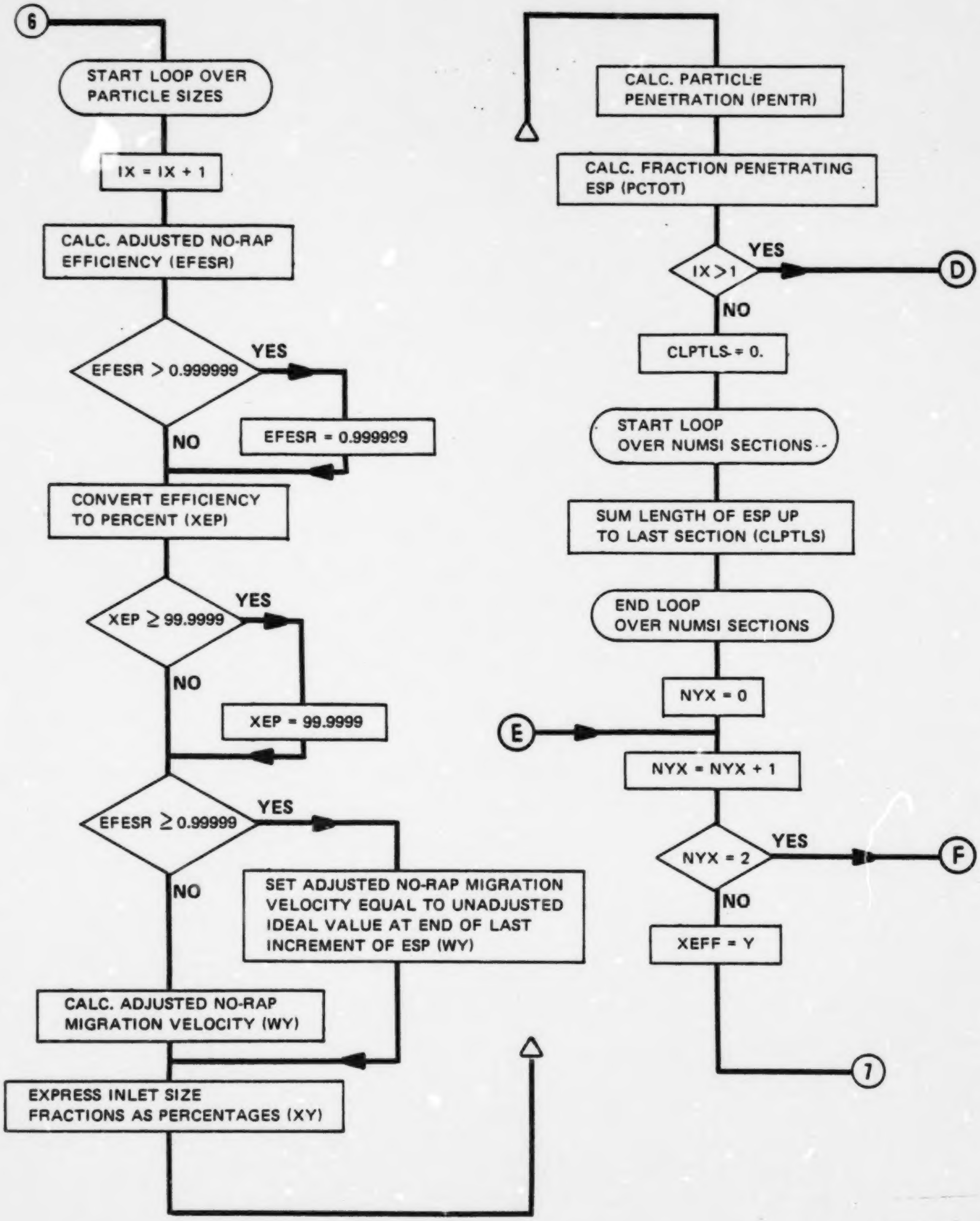

6
START LOOP OVER PARTICLE SIZES
IX = IX + 1
CALC. ADJUSTED NO-RAP EFFICIENCY (EFESR)
EFESR > 0.999999
YES
NO
EFESR = 0.999999
CONVERT EFFICIENCY TO PERCENT (XEP)
XEP ≥ 99.9999
YES
NO
XEP = 99.9999
EFESR ≥ 0.99999
YES
NO
SET ADJUSTED NO-RAP MIGRATION VELOCITY EQUAL TO UNADJUSTED IDEAL VALUE AT END OF LAST INCREMENT OF ESP (WY)
CALC. ADJUSTED NO-RAP MIGRATION VELOCITY (WY)
EXPRESS INLET SIZE FRACTIONS AS PERCENTAGES (XY)
CALC. PARTICLE PENETRATION (PENTR)
CALC. FRACTION PENETRATING ESP (PCTOT)
IX>1
YES
D
NO
CLPTLS = 0.
START LOOP OVER NUMSI SECTIONS
SUM LENGTH OF ESP UP TO LAST SECTION (CLPTLS)
END LOOP OVER NUMSI SECTIONS
NYX = 0
E
NYX = NYX + 1
NYX = 2
YES
F
NO
XEFF = Y
7

Figure 22. Flow chart for subroutine ADJUST (Sheet 7 of 13).

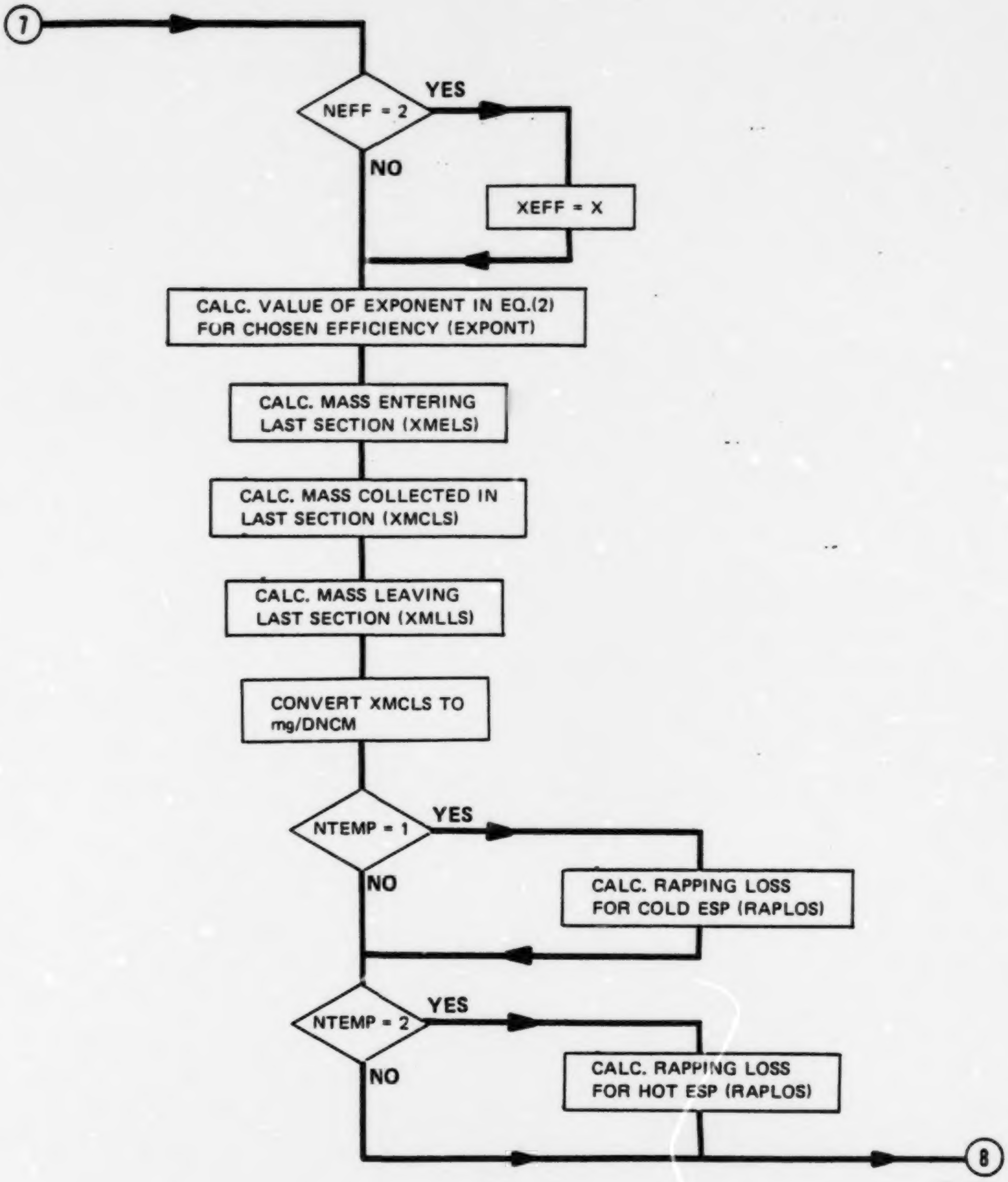
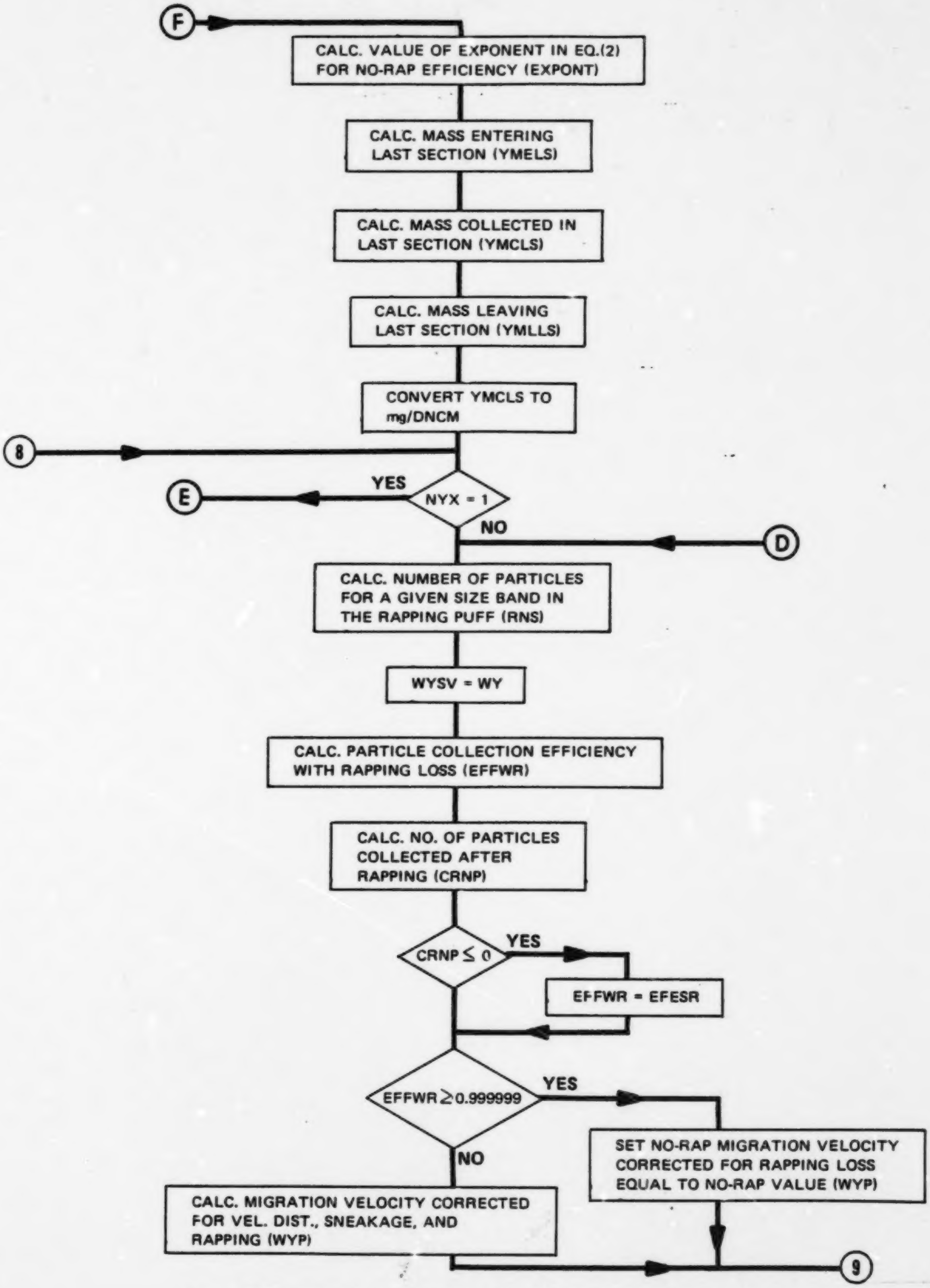

7
NEFF = 2
YES
NO
XEFF = X
CALC. VALUE OF EXPONENT IN EQ.(2) FOR CHOSEN EFFICIENCY (EXPONT)
CALC. MASS ENTERING LAST SECTION (XMELS)
CALC. MASS COLLECTED IN LAST SECTION (XMCLS)
CALC. MASS LEAVING LAST SECTION (XMLLS)
CONVERT XMCLS TO mg/DNCM
NTEMP = 1
YES
NO
CALC. RAPPING LOSS FOR COLD ESP (RAPLOS)
NTEMP = 2
YES
NO
CALC. RAPPING LOSS FOR HOT ESP (RAPLOS)
8

Figure 22. Flow chart for subroutine ADJUST (Sheet 8 of 13).



F
CALC. VALUE OF EXPONENT IN EQ.(2) FOR NO-RAP EFFICIENCY (EXPONT)
CALC. MASS ENTERING LAST SECTION (YMELS)
CALC. MASS COLLECTED IN LAST SECTION (YMCLS)
CALC. MASS LEAVING LAST SECTION (YMLLS)
CONVERT YMCLS TO mg/DNCM
8
YES
E
NYX = 1
NO
D
CALC. NUMBER OF PARTICLES FOR A GIVEN SIZE BAND IN THE RAPPING PUFF (RNS)
WYSV = WY
CALC. PARTICLE COLLECTION EFFICIENCY WITH RAPPING LOSS (EFFWR)
CALC. NO. OF PARTICLES COLLECTED AFTER RAPPING (CRNP)
CRNP ≤ 0
YES
EFFWR = EFESR
EFFWR ≥ 0.999999
YES
NO
SET NO-RAP MIGRATION VELOCITY CORRECTED FOR RAPPING LOSS EQUAL TO NO-RAP VALUE (WYP)
CALC. MIGRATION VELOCITY CORRECTED FOR VEL. DIST., SNEAKAGE, AND RAPPING (WYP)
9

Figure 22. Flow chart for subroutine ADJUST (Sheet 9 of 13).

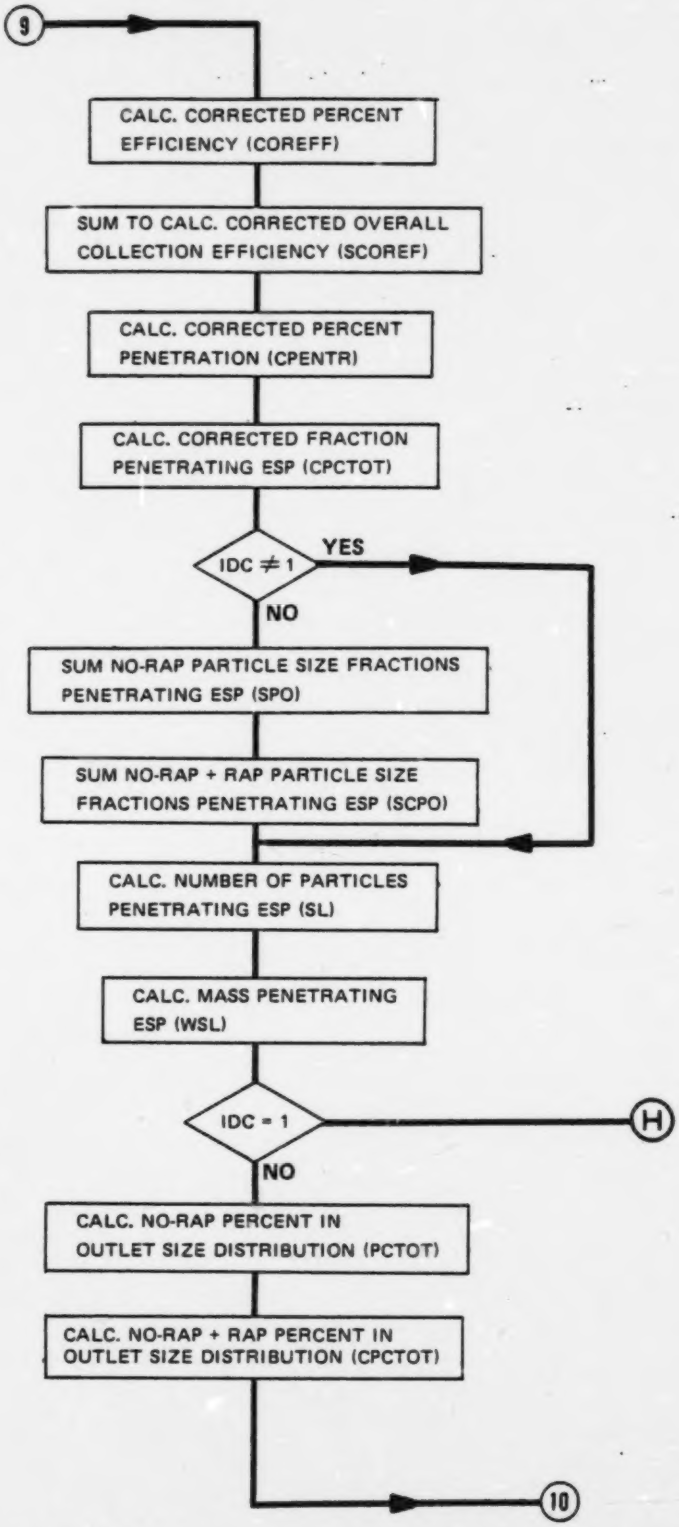

9
CALC. CORRECTED PERCENT EFFICIENCY (COREFF)
SUM TO CALC. CORRECTED OVERALL COLLECTION EFFICIENCY (SCOREF)
CALC. CORRECTED PERCENT PENETRATION (CPENTR)
CALC. CORRECTED FRACTION PENETRATING ESP (CPCTOT)
IDC ≠ 1
YES
NO
SUM NO-RAP PARTICLE SIZE FRACTIONS PENETRATING ESP (SPO)
SUM NO-RAP + RAP PARTICLE SIZE FRACTIONS PENETRATING ESP (SCPO)
CALC. NUMBER OF PARTICLES PENETRATING ESP (SL)
CALC. MASS PENETRATING ESP (WSL)
IDC = 1
H
NO
CALC. NO-RAP PERCENT IN OUTLET SIZE DISTRIBUTION (PCTOT)
CALC. NO-RAP + RAP PERCENT IN OUTLET SIZE DISTRIBUTION (CPCTOT)
10

Figure 22. Flow chart for subroutine ADJUST (Sheet 10 of 13).

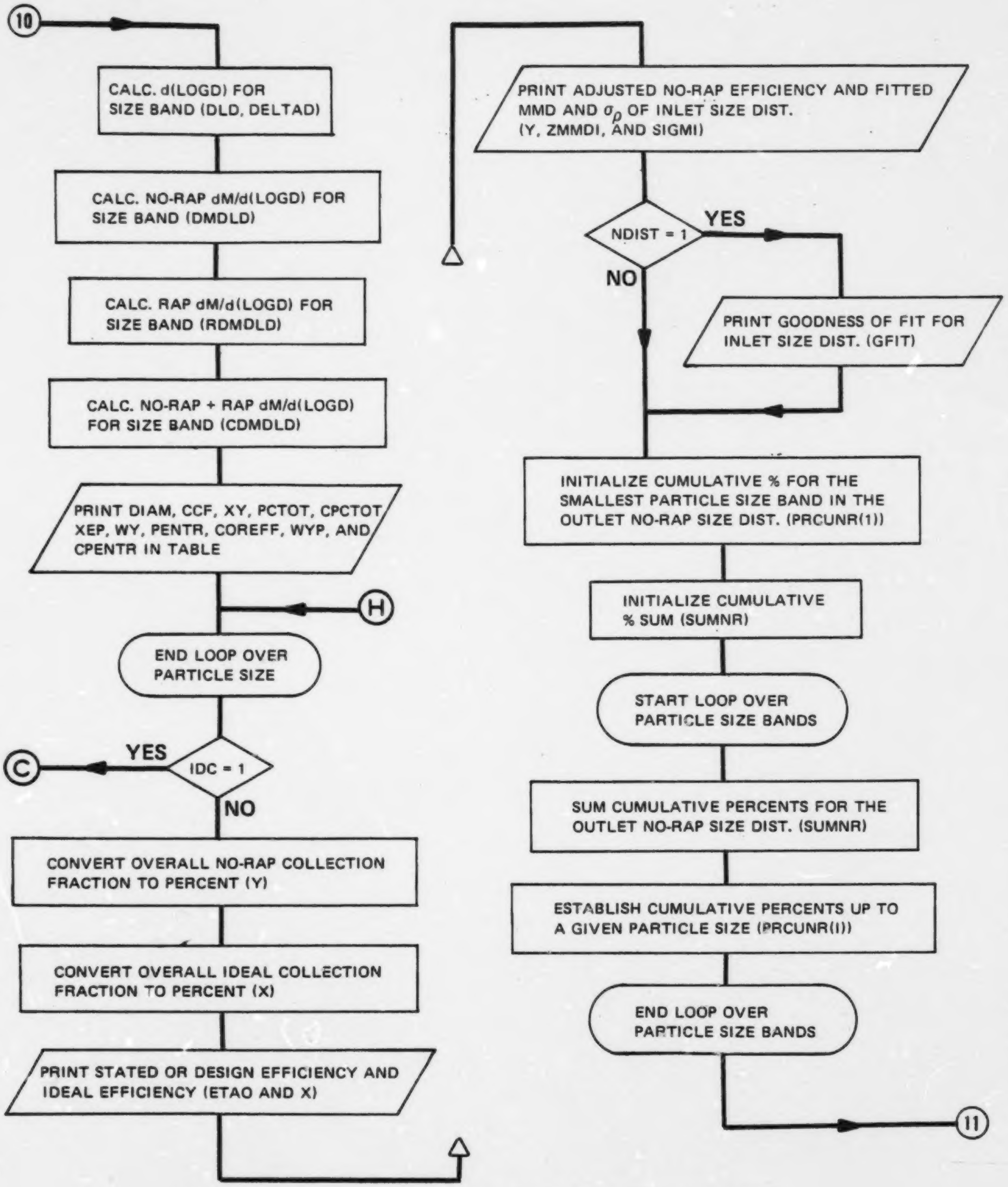

10
CALC. d(LOGD) FOR SIZE BAND (DLD, DELTAD)
CALC. NO-RAP dM/d(LOGD) FOR SIZE BAND (DMDLD)
CALC. RAP dM/d(LOGD) FOR SIZE BAND (RDMDLD)
CALC. NO-RAP + RAP dM/d(LOGD) FOR SIZE BAND (CDMDLD)
PRINT DIAM, CCF, XY, PCTOT, CPCTOT XEP, WY, PENTR, COREFF, WYP, AND CPENTR IN TABLE
H
END LOOP OVER PARTICLE SIZE
IDC = 1
YES
C
NO
CONVERT OVERALL NO-RAP COLLECTION FRACTION TO PERCENT (Y)
CONVERT OVERALL IDEAL COLLECTION FRACTION TO PERCENT (X)
PRINT STATED OR DESIGN EFFICIENCY AND IDEAL EFFICIENCY (ETAO AND X)
PRINT ADJUSTED NO-RAP EFFICIENCY AND FITTED MMD AND σ_p OF INLET SIZE DIST. (Y, ZMMDI, AND SIGMI)
NDIST = 1
YES
NO
PRINT GOODNESS OF FIT FOR INLET SIZE DIST. (GFIT)
INITIALIZE CUMULATIVE % FOR THE SMALLEST PARTICLE SIZE BAND IN THE OUTLET NO-RAP SIZE DIST. (PRCUNR(1))
INITIALIZE CUMULATIVE % SUM (SUMNR)
START LOOP OVER PARTICLE SIZE BANDS
SUM CUMULATIVE PERCENTS FOR THE OUTLET NO-RAP SIZE DIST. (SUMNR)
ESTABLISH CUMULATIVE PERCENTS UP TO A GIVEN PARTICLE SIZE (PRCUNR(I))
END LOOP OVER PARTICLE SIZE BANDS
11

Figure 22. Flow chart for subroutine ADJUST (Sheet 11 of 13).

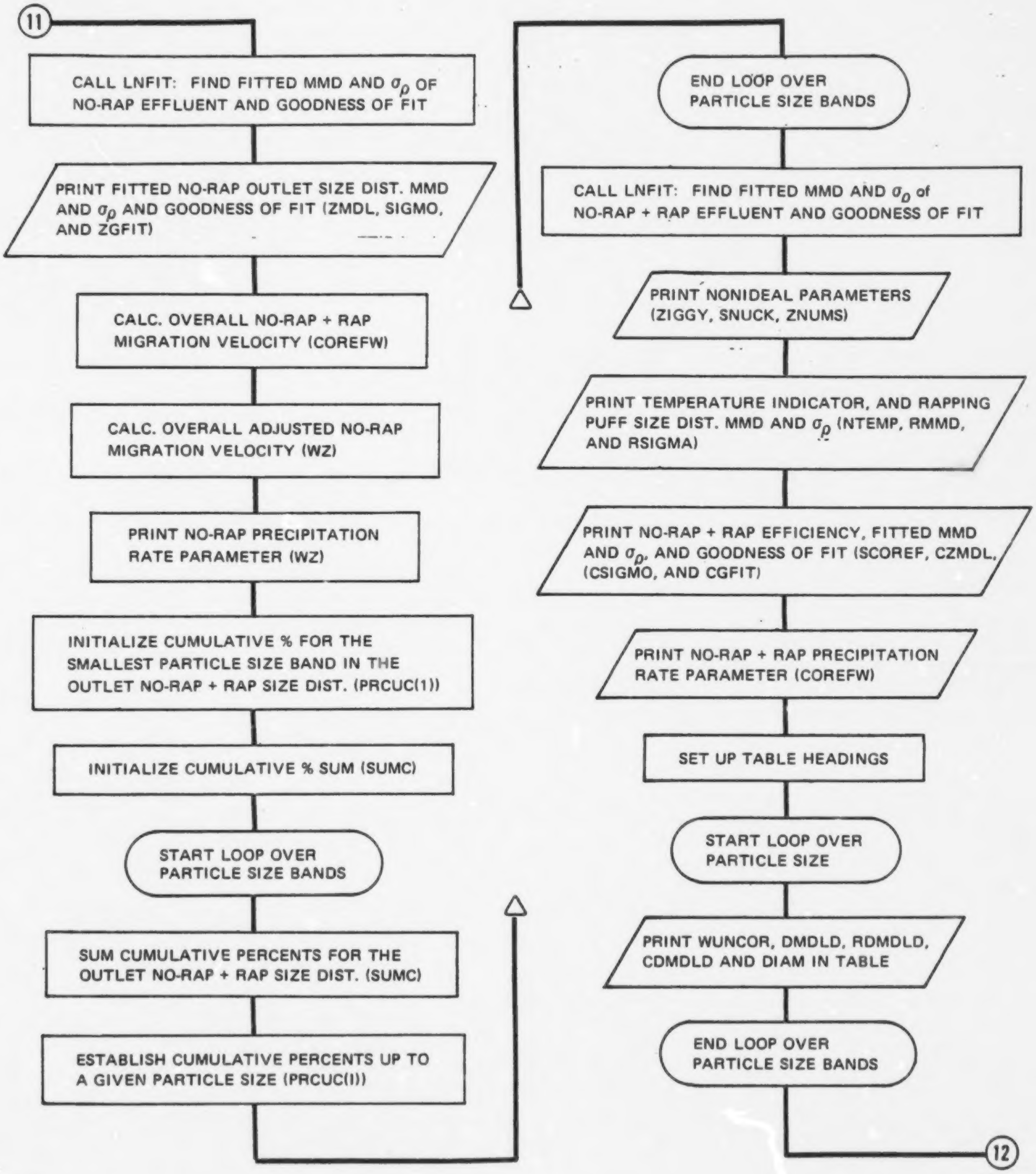

11
CALL LNFIT: FIND FITTED MMD AND σ_ρ OF NO-RAP EFFLUENT AND GOODNESS OF FIT
PRINT FITTED NO-RAP OUTLET SIZE DIST. MMD AND σ_ρ AND GOODNESS OF FIT (ZMDL, SIGMO, AND ZGFIT)
CALC. OVERALL NO-RAP + RAP MIGRATION VELOCITY (COREFW)
CALC. OVERALL ADJUSTED NO-RAP MIGRATION VELOCITY (WZ)
PRINT NO-RAP PRECIPITATION RATE PARAMETER (WZ)
INITIALIZE CUMULATIVE % FOR THE SMALLEST PARTICLE SIZE BAND IN THE OUTLET NO-RAP + RAP SIZE DIST. (PRCUC(1))
INITIALIZE CUMULATIVE % SUM (SUMC)
START LOOP OVER PARTICLE SIZE BANDS
SUM CUMULATIVE PERCENTS FOR THE OUTLET NO-RAP + RAP SIZE DIST. (SUMC)
ESTABLISH CUMULATIVE PERCENTS UP TO A GIVEN PARTICLE SIZE (PRCUC(I))
END LOOP OVER PARTICLE SIZE BANDS
CALL LNFIT: FIND FITTED MMD AND σ_ρ of NO-RAP + RAP EFFLUENT AND GOODNESS OF FIT
PRINT NONIDEAL PARAMETERS (ZIGGY, SNUCK, ZNUMS)
PRINT TEMPERATURE INDICATOR, AND RAPPING PUFF SIZE DIST. MMD AND σ_ρ (NTEMP, RMMD, AND RSIGMA)
PRINT NO-RAP + RAP EFFICIENCY, FITTED MMD AND σ_ρ, AND GOODNESS OF FIT (SCOREF, CZMDL, (CSIGMO, AND CGFIT)
PRINT NO-RAP + RAP PRECIPITATION RATE PARAMETER (COREFW)
SET UP TABLE HEADINGS
START LOOP OVER PARTICLE SIZE
PRINT WUNCOR, DMDLD, RDMDLD, CDMDLD AND DIAM IN TABLE
END LOOP OVER PARTICLE SIZE BANDS
12

Figure 22. Flow chart for subroutine ADJUST (Sheet 12 of 13).

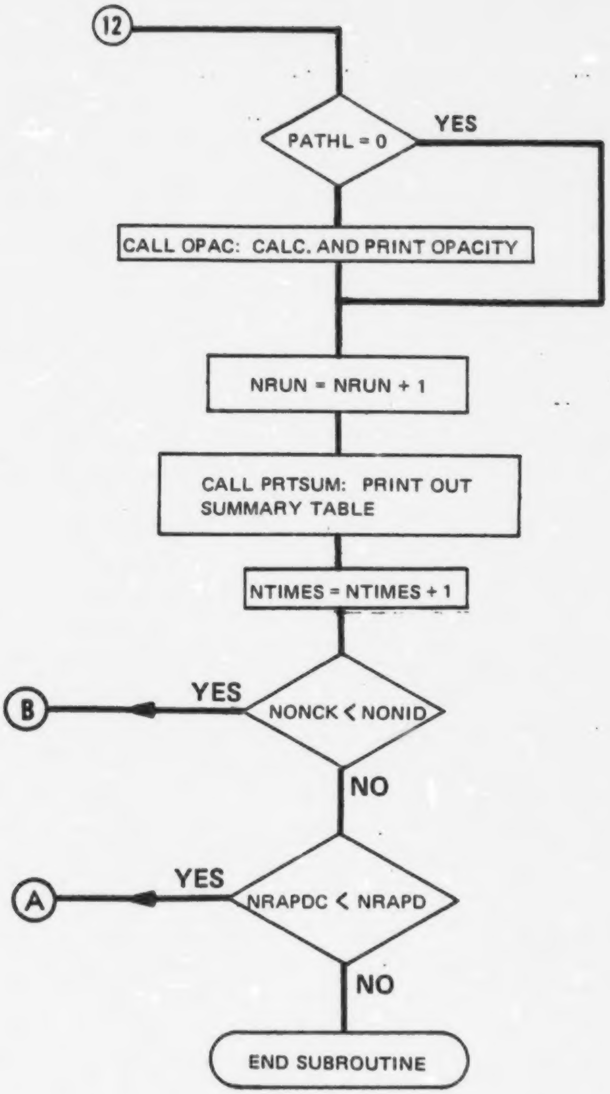

12
PATHL = 0
YES
CALL OPAC: CALC. AND PRINT OPACITY
NRUN = NRUN + 1
CALL PRTSUM: PRINT OUT SUMMARY TABLE
NTIMES = NTIMES + 1
B
YES
NONCK < NONID
NO
A
YES
NRAPDC < NRAPD
NO
END SUBROUTINE

Figure 22. Flow chart for subroutine ADJUST (Sheet 13 of 13).

DXS(I) - Number of particles per unit volume of gas for a given particle size band which are removed from the gas stream under unadjusted, ideal conditions (#/m^3).

XMV(I) - Unadjusted, ideal migration velocity for a given particle size band (cm/sec).

PCNT(I) - Fraction by mass of a given particle size band in the inlet particle size distribution.

CCF(I) - Cunningham correction factor for a given particle size band.

LSECT(J) - Number of increments to be taken in a given electrical section.

LINCS(J) - Incremental length size to be taken in a given electrical section (ft).

PS(J) - Gas pressure in a given electrical section (atm).

VG - Gas volume flow rate (m^3/sec).

ATOTAL - Total collection plate area (m^2).

DD - Mass density of the particles (kg/m^3).

ETAO - Estimated or design efficiency (%).

DL - Inlet mass loading (kg/m^3).

PL - Total electrical length of the precipitator (m).

RHO - Resistivity of collected particulate layer (ohm-m).

NS - Number of size bands in inlet particle size histogram.

ZMMDI - Fitted mass median diameter of the inlet particle size distribution (m).

SIGMI - Fitted geometric standard deviation of the inlet particle size distribution.

NONID - Total number of sets of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered.

NRAPD - Total number of rapping puff size distributions to be considered.

TDK - Temperature of the gas stream (°K).

NUMSEC - Number of electrical sections in the direction of gas flow.

NEFF - Indicator which can have the values of 1 and 2. If NEFF = 1, then the total mass reentrained at the outlet due to rapping is determined from the mass collected in the last field under adjusted no-rap conditions. If NEFF = 2, then the total mass reentrained at the outlet due to rapping is determined from the mass which would be collected in the last field under unadjusted, ideal conditions.

NTEMP - Indicator which can have the values of 1 and 2. If NTEMP = 1, then the mass reentrained due to rapping is calculated based on equation (24) for a cold-side precipitator. If NTEMP = 2, then the mass reentrained due to rapping is calculated based on equation (25) for a hot-side precipitator.

GFIT - Log-normal goodness of fit parameter for the fitted inlet particle size distribution.

VOS(J) - Applied voltage in a given electrical section (V).

TCS(J) - Total current in a given electrical section (A).

ENDPT(K) - Endpoints of the particle size band intervals in the inlet particle size histogram (μm).

NENDPT - Number of endpoints in the inlet particle size distribution histogram.

ARD50(L) - Specified mass median diameter used to describe a log-normal particle size distribution for the rapping puff (μm).

ARSIGM(L) - Specified geometric standard deviation used to describe a log-normal particle size distribution for the rapping puff.

ASNUCK(M) - Specified fraction of gas flow which bypasses the electrified region in each baffled stage of the precipitator and/or fraction of the mass collected in each stage of the precipitator which is reentrained due to factors other than rapping.

AZNUMS(M) - Specified number of baffled stages in the precipitator.

AZIGGY(M) - Specified normalized standard deviation of the inlet gas velocity distribution.

NPRNT - Indicator whose value must be that which designates the print unit for a given machine.

SCOREF - Overall mass collection efficiency under no-rap + rap conditions (%).

CZMDL - Fitted mass median diameter of the outlet particle size distribution under no-rap + rap conditions (μm).

CSIGMO - Fitted geometric standard deviation of the outlet particle size distribution under no-rap + rap conditions.

NRUN - Indicator that specifies which set of nonideal conditions is under consideration.

SNUCK - Particular value of ASNUCK(M).

ZIGGY - Particular value of AZIGGY(M).

RMMD - Particular value of ARD50(L) [μm].

RSIGMA - Particular value of ARSIGM(L).

D50 - Same as ZMMDI (μm).

SIGMAP - Same as SIGMI.

PATHL - Pathlength for calculation of opacity.

Of the above variables, the values of the following must be provided by the main program: DIAM, ONO, DXS, XMV, PCNT, CCF, LSECT, LINCS, PS, VG, ATOTAL, DD, ETAO, DL, PL, RHO, NS, ZMMDI, SIGMI, NONID, NRAPD, TDK, NUMSEC, NEFF, NTEMP, GFIT, VOS, TCS, ENDPT, NENDPT, ARD50, ARSIGM, ASNUCK, AZNUMS, AZIGGY, NPRNT, D50, SIGMAP, and PATHL. The values of the following variables are determined in the subroutine: SCOREF, CZMDL, CSIGMO, NRUN, SNUCK, ZIGGY, RMMD, and RSIGMA. The values of these variables must be supplied to subroutine PRTSUM. In the above arrays, I, J, K, L, and M can not exceed values of 20, 10, 21, 10, and 15, respectively. The restrictions on I, J, K, L, and M limit the number of particle size bands, the number of electrical sections, the number of particle diameters in the inlet particle size distribution, the number of rapping puff particle size distributions, and the number of sets of nonideal conditions of σ_g and S, respectively.

Subroutine WADJST

This subroutine adjusts the no-rap migration velocities by applying the empirical correction factors given in Figure 7. These correction factors and their corresponding particle sizes are tabulated for 24 particle diameters between 0.2 μm and 4.5 μm in data statements. Table 2 shows the particle sizes and correction factors which are tabulated. Correction factors for no-rap migration velocities for particle diameters in the range 0.2 μm - 4.5 μm are found by interpolating the table. No-rap

TABLE 2. PARTICLE SIZES AND CORRECTION FACTORS FOR NO-RAP MIGRATION VELOCITIES TABULATED IN SUBROUTINE WADJST

Particle Diameter (μm)	Correction Factor	Particle Diameter (μm)	Correction Factor
0.20	2.430	0.80	1.790
0.25	2.325	0.85	1.760
0.30	2.240	0.90	1.740
0.35	2.170	0.95	1.710
0.40	2.110	1.00	1.685
0.45	2.050	1.50	1.500
0.50	2.000	2.00	1.370
0.55	1.965	2.50	1.270
0.60	1.920	3.00	1.180
0.65	1.885	3.50	1.115
0.70	1.850	4.00	1.050
0.75	1.820	4.50	1.000

migration velocities outside this range are left unchanged. Based on the adjusted no-rap migration velocities, the subroutine calculates for each particle size an adjusted no-rap collection fraction and the number of particles removed.

Figure 23 shows a detailed flow chart for this subroutine. This subroutine is called by subroutine ADJUST and all information which is transmitted between these subprograms is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

DIAM(I) - Midpoint of a given particle size band (m).

I - Index which specifies the different particle diameters.

WY - Enters the subroutine as a no-rap migration velocity and returns as an adjusted no-rap migration velocity (cm/sec).

ONO(I) - Number of particles per unit volume of gas for a given particle size band entering the precipitator (#/m^3).

PXS(I) - Number of particles per unit volume of gas for a given particle size band which are removed from the gas stream under adjusted no-rap conditions (#/m^3).

ATOTAL - Total collection plate area (m^2).

VG - Gas volume flow rate (m^3/sec).

EFESR - Enters the subroutine as a no-rap collection fraction and returns as an adjusted no-rap collection fraction.

All of the above variables must be supplied by subroutine ADJUST. The values of WY and EFESR are replaced by new values for particle sizes in the range 0.2 - 4.5 μm. In all of the uses above, I can not exceed a value of 20. The restriction on the value of I limits the number of particle size bands.

Subroutine LNDIST

This subroutine constructs a particle size distribution histogram for a specified log-normal distribution. For specified particle diameters, the fraction in each particle size band and cumulative fraction less than each particle size are determined. In order to use this subroutine, subroutine QTFE must be supplied.

The log-normal distribution function $[f_{L-N}(z)]$ is given by the expression

$$f_{L-N}(z) = \frac{1}{\sigma_z \sqrt{2\pi}} \quad \text{EXP} \left[- \frac{(z-\bar{z})^2}{2\sigma_z{}^2} \right] \quad , \qquad (59)$$

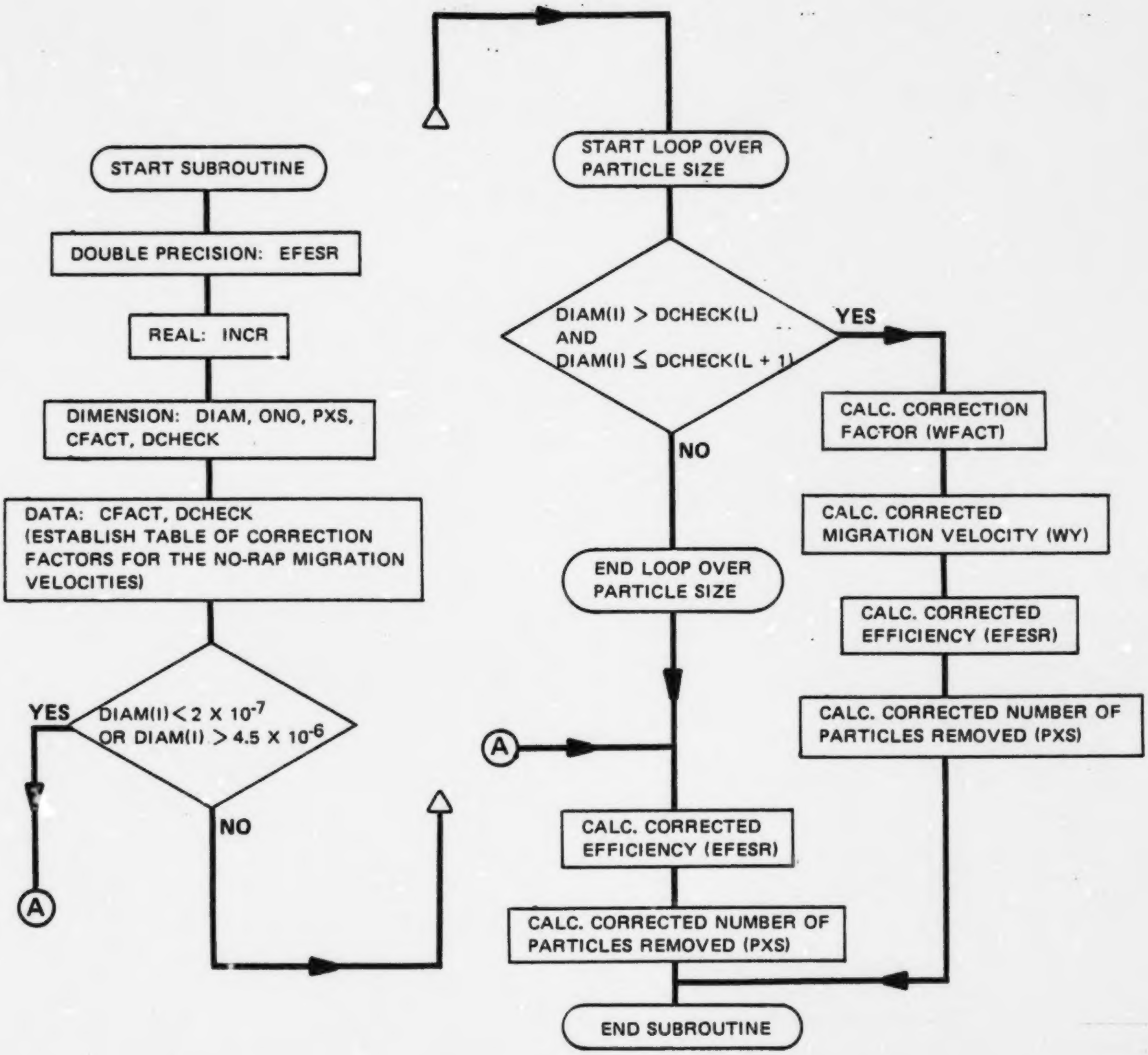

START SUBROUTINE
DOUBLE PRECISION: EFESR
REAL: INCR
DIMENSION: DIAM, ONO, PXS, CFACT, DCHECK
DATA: CFACT, DCHECK (ESTABLISH TABLE OF CORRECTION FACTORS FOR THE NO-RAP MIGRATION VELOCITIES)
YES
DIAM(I) < 2 X 10^{-7} OR DIAM(I) > 4.5 X 10^{-6}
NO
A
START LOOP OVER PARTICLE SIZE
DIAM(I) > DCHECK(L) AND DIAM(I) ≤ DCHECK(L + 1)
YES
NO
CALC. CORRECTION FACTOR (WFACT)
CALC. CORRECTED MIGRATION VELOCITY (WY)
CALC. CORRECTED EFFICIENCY (EFESR)
CALC. CORRECTED NUMBER OF PARTICLES REMOVED (PXS)
END LOOP OVER PARTICLE SIZE
A
CALC. CORRECTED EFFICIENCY (EFESR)
CALC. CORRECTED NUMBER OF PARTICLES REMOVED (PXS)
END SUBROUTINE

Figure 23. Flow chart for subroutine WADJST.

where

$$\sigma_z = \ln \sigma_p \quad , \tag{60}$$

$$z = \ln d \quad , \tag{61}$$

$$\bar{z} = \ln d_{50} \quad , \tag{62}$$

and

d = particle diameter (μm),

d_{50} = mass median diameter for the distribution (μm),

σ_p = geometric standard deviation for the distribution,

z = independent variable for the log-normal distribution,

$\bar{z}$ = mean value of z, and

σ_z = standard deviation of z.

$f_{L-N}(z)\, dz$ represents the amount of mass (or other variable if desired) in the range between z and $z + dz$. The distribution is completely described by specifying the values of d_{50} and σ_p.

The subroutine constructs the log-normal distribution histogram by (1) determining the total mass contained between $z_1 = \ln 0.01$ and $z_n = \ln 1000.0$, (2) calculating the mass contained in each size band specified by the user, and (3) calculating the ratios of the mass contained in each size band to the total mass. The total mass (M) contained in the distribution is obtained in cumulative steps in the form

$$M = \int_{z_1}^{z_2} f_{L-N}(z)dz + \int_{z_2}^{z_3} f_{L-N}(z)dz + \int_{z_3}^{z_4} f_{L-N}(z)dz$$

$$+\cdots\cdots+ \int_{z_{n-2}}^{z_{n-1}} f_{L-N}(z)dz + \int_{z_{n-1}}^{z_n} f_{L-N}(z)dz \quad . \tag{63}$$

The integrals in equation (63) are evaluated numerically by calling subroutine QTFE which utilizes the Trapezoidal Rule. Each integration is performed by dividing the size band into 99 intervals and evaluating the integrand at 100 points. The value of each integral is stored as well as the cumulative sum. The user specifies the particle diameters in μm which correspond to the values of z from z_2 to z_{n-1} where $z_2 > -4.605$ and $z_{n-1} < 6.908$ ($d_2 > 0.01$ and $d_{n-1} < 1000.0$).

The mass fractions (F_i) for the size bands in equation (63) are obtained from the expressions

$$F_1 = \left(\int_{z_1}^{z_2} f_{L-N}(z)dz \right) /M$$

$$F_2 = \left(\int_{z_2}^{z_3} f_{L-N}(z)dz \right) /M$$

$$\begin{matrix} \vdots & & \vdots \end{matrix}$$

$$F_{n-1} = \left(\int_{z_{n-1}}^{z_n} f_{L-N}(z)dz \right) /M \quad , \qquad (64)$$

where there are n-1 size bands. Since the size bands specified by the user are contained in the range from z_2 to z_{n-1}, the excess mass fractions in the size bands z_1 to z_2 and z_{n-1} to z_n are added to the mass fraction in the size band z_{n-2} to z_{n-1} for the histogram which is returned from the subroutine. This is done to ensure that the size distribution used in the model accounts for 100% of the mass.

The cumulative mass fractions (S_i) for the specified diameters and size bands are obtained from

$$S_2 = F_1$$

$$S_3 = \sum_{i=1}^{2} F_i$$

$$S_4 = \sum_{i=1}^{3} F_i$$

$$\vdots \qquad \vdots$$

$$S_{n-1} = \sum_{i=1}^{n-1} F_i + \left(1 - \sum_{i=1}^{n-1} F_i \right) , \tag{65}$$

where the cumulative mass fraction less than the largest specified diameter is constrained to be a value of 1 by adjusting the mass fraction in the size band from z_{n-2} to z_{n-1}.

Figure 24 shows a detailed flowchart for this subroutine. This subroutine is called by the main program and subroutine ADJUST. Information which is transmitted to and from this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

D50 - Specified mass median diameter for a log-normal distribution (μm),

SIGMAP - Specified geometric standard deviation for a log-normal distribution,

PRCU(I) - Cumulative mass fractions for the log-normal distribution, and

PCNT(J) - Mass fraction in a given size band of the log-normal distribution.

The following is a list of the necessary variables which are in common with the main program and subroutine ADJUST.

NS - Number of specified particle size bands in the histogram for the log-normal distribution,

ENDPT(I) - Specified endpoints of the particle size band intervals in the histogram for the log-normal distribution (μm), and

NENDPT - Specified number of endpoints in the histogram for the log-normal distribution.

Of the above variables, the values of the following must be provided by the calling program or subprogram: D50, SIGMAP, NS, ENDPT, and NENDPT. PRCU and PCNT are determined in the subroutine. I and J can not exceed values of 21 and 20, respectively. The

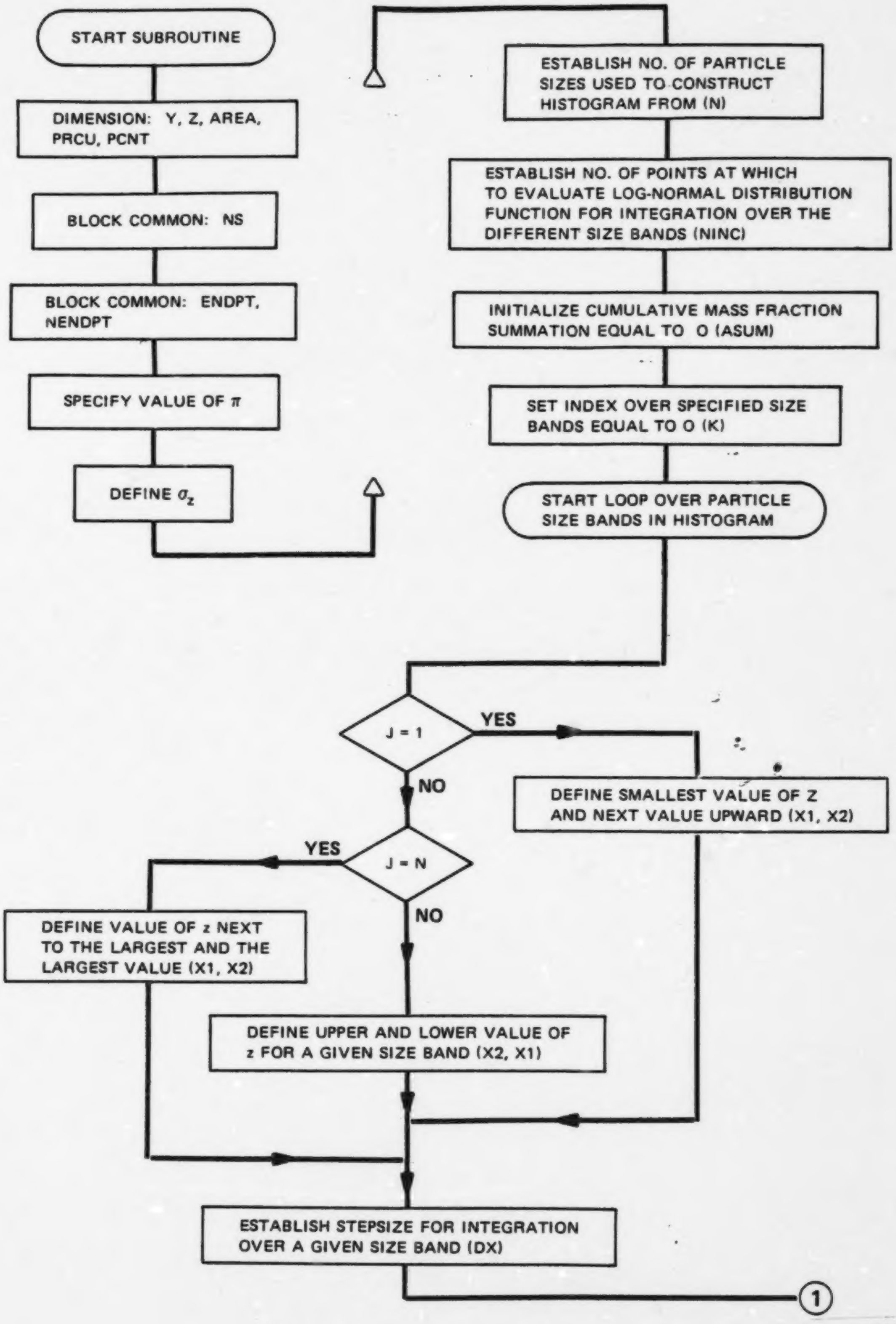

START SUBROUTINE
DIMENSION: Y, Z, AREA, PRCU, PCNT
BLOCK COMMON: NS
BLOCK COMMON: ENDPT, NENDPT
SPECIFY VALUE OF π
DEFINE σz
ESTABLISH NO. OF PARTICLE SIZES USED TO CONSTRUCT HISTOGRAM FROM (N)
ESTABLISH NO. OF POINTS AT WHICH TO EVALUATE LOG-NORMAL DISTRIBUTION FUNCTION FOR INTEGRATION OVER THE DIFFERENT SIZE BANDS (NINC)
INITIALIZE CUMULATIVE MASS FRACTION SUMMATION EQUAL TO O (ASUM)
SET INDEX OVER SPECIFIED SIZE BANDS EQUAL TO O (K)
START LOOP OVER PARTICLE SIZE BANDS IN HISTOGRAM
J = 1
YES
NO
DEFINE SMALLEST VALUE OF Z AND NEXT VALUE UPWARD (X1, X2)
YES
J = N
NO
DEFINE VALUE OF z NEXT TO THE LARGEST AND THE LARGEST VALUE (X1, X2)
DEFINE UPPER AND LOWER VALUE OF z FOR A GIVEN SIZE BAND (X2, X1)
ESTABLISH STEPSIZE FOR INTEGRATION OVER A GIVEN SIZE BAND (DX)
①

Figure 24. Flow chart for subroutine LNDIST (Sheet 1 of 3).

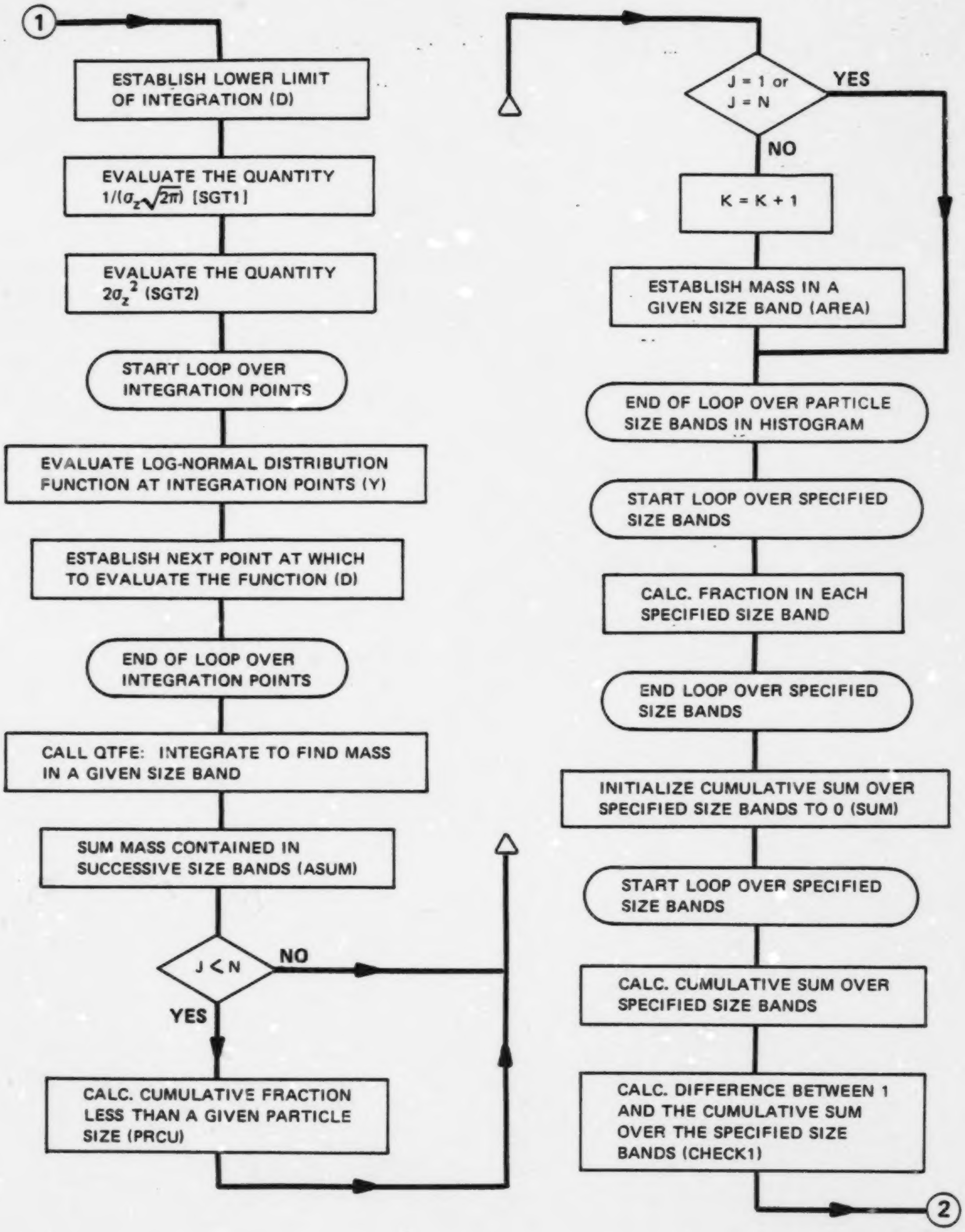

①
ESTABLISH LOWER LIMIT OF INTEGRATION (D)
EVALUATE THE QUANTITY $1/(\sigma_z\sqrt{2\pi})$ [SGT1]
EVALUATE THE QUANTITY $2\sigma_z^2$ (SGT2)
START LOOP OVER INTEGRATION POINTS
EVALUATE LOG-NORMAL DISTRIBUTION FUNCTION AT INTEGRATION POINTS (Y)
ESTABLISH NEXT POINT AT WHICH TO EVALUATE THE FUNCTION (D)
END OF LOOP OVER INTEGRATION POINTS
CALL QTFE: INTEGRATE TO FIND MASS IN A GIVEN SIZE BAND
SUM MASS CONTAINED IN SUCCESSIVE SIZE BANDS (ASUM)
J < N
NO
YES
CALC. CUMULATIVE FRACTION LESS THAN A GIVEN PARTICLE SIZE (PRCU)
J = 1 or J = N
YES
NO
K = K + 1
ESTABLISH MASS IN A GIVEN SIZE BAND (AREA)
END OF LOOP OVER PARTICLE SIZE BANDS IN HISTOGRAM
START LOOP OVER SPECIFIED SIZE BANDS
CALC. FRACTION IN EACH SPECIFIED SIZE BAND
END LOOP OVER SPECIFIED SIZE BANDS
INITIALIZE CUMULATIVE SUM OVER SPECIFIED SIZE BANDS TO 0 (SUM)
START LOOP OVER SPECIFIED SIZE BANDS
CALC. CUMULATIVE SUM OVER SPECIFIED SIZE BANDS
CALC. DIFFERENCE BETWEEN 1 AND THE CUMULATIVE SUM OVER THE SPECIFIED SIZE BANDS (CHECK1)
②

Figure 24. Flow chart for subroutine LNDIST (Sheet 2 of 3).

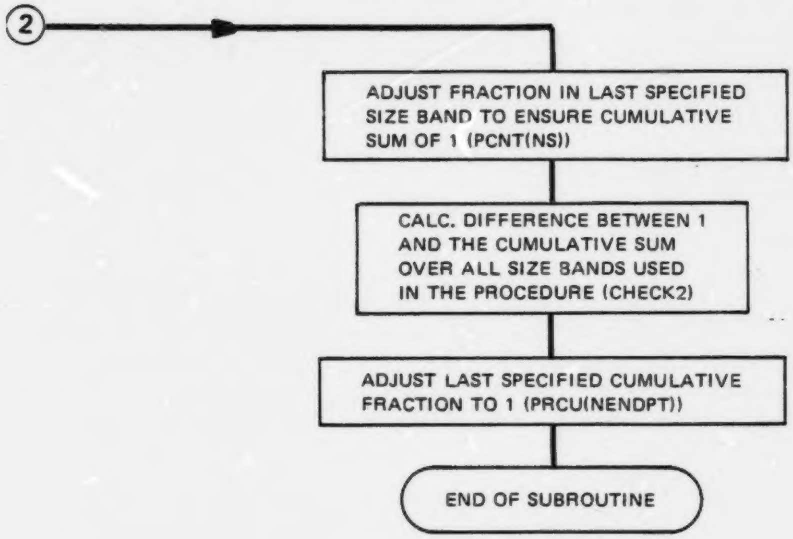

2
ADJUST FRACTION IN LAST SPECIFIED SIZE BAND TO ENSURE CUMULATIVE SUM OF 1 (PCNT(NS))
CALC. DIFFERENCE BETWEEN 1 AND THE CUMULATIVE SUM OVER ALL SIZE BANDS USED IN THE PROCEDURE (CHECK2)
ADJUST LAST SPECIFIED CUMULATIVE FRACTION TO 1 (PRCU(NENDPT))
END OF SUBROUTINE

Figure 24. Flow chart for subroutine LNDIST (Sheet 3 of 3).

restrictions on I and J limit the number of particle diameters in the inlet particle size distribution and the number of particle size bands, respectively.

Subroutine QTFE

This subroutine performs the integration of an equidistantly tabulated function by the trapezoidal rule.[37] Cumulative integral values (Z_i) are determined by

$$Z_i = Z_i(x) = \int_a^{x_i} y(x)dx \quad , \qquad (66)$$

where $x_i = a + (i-1)h$ and $i=1,2,\cdots,n$. The function values y_i are tabulated at the equidistant points x_i, where h is the increment size for the integration. Starting with the integral value $Z_1 = 0$, successive integral values Z_i $(i=2,3,\cdots,n)$ are computed by using the trapezoidal rule in the form

$$Z_i = Z_{i-1} + \frac{h}{2}(y_i + y_{i-1}) \quad . \qquad (67)$$

In applying the trapezoidal rule, it is assumed that the function to be integrated is continuous and can be differentiated at least twice.

This subroutine is called by subroutine LNDIST. Figure 25 shows a detailed flow chart for this subroutine. All information which is transmitted between subroutine LNDIST and this subroutine is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

DX - Increment size for the integration.

Y(I) - Table of function values at the equidistant points used in the integration procedure.

Z(I) - Cumulative integral values.

NINC - Number of points at which the function to be integrated is evaluated.

Of the above variables, the values of DX, Y, and NINC must be provided by the calling program (subroutine LNDIST). The values of Z are returned from subroutine QTFE.

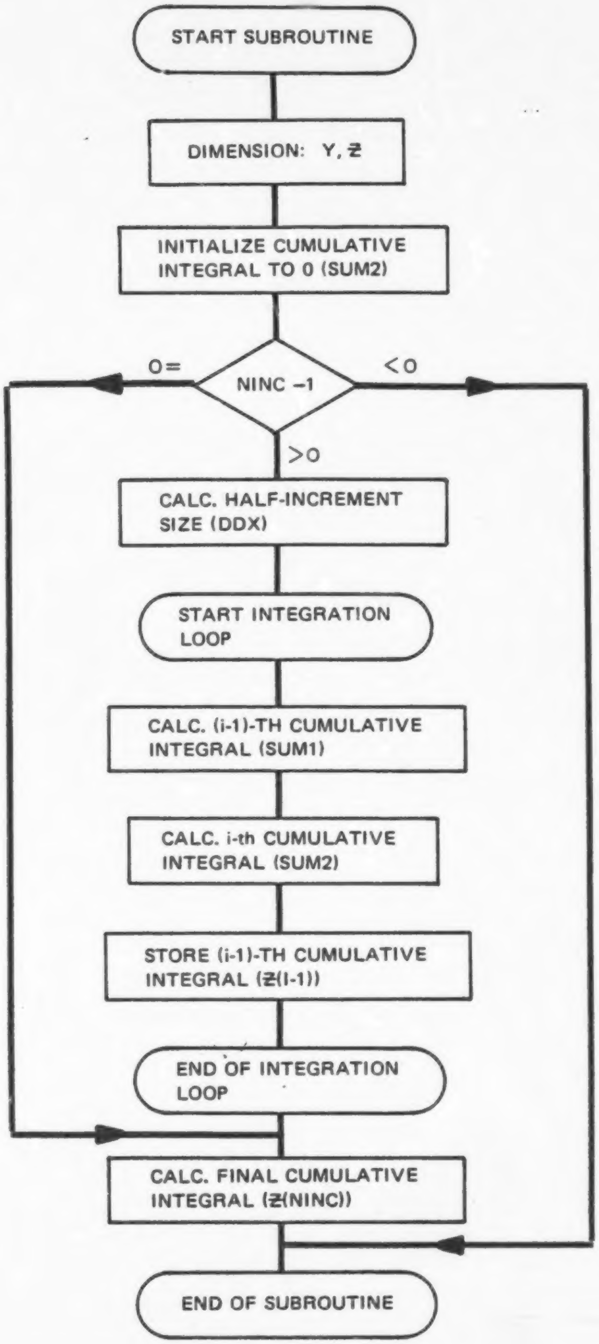

START SUBROUTINE
DIMENSION: Y, Z
INITIALIZE CUMULATIVE INTEGRAL TO 0 (SUM2)
NINC −1
0=
<0
>0
CALC. HALF-INCREMENT SIZE (DDX)
START INTEGRATION LOOP
CALC. (i-1)-TH CUMULATIVE INTEGRAL (SUM1)
CALC. i-th CUMULATIVE INTEGRAL (SUM2)
STORE (i-1)-TH CUMULATIVE INTEGRAL (Z(I-1))
END OF INTEGRATION LOOP
CALC. FINAL CUMULATIVE INTEGRAL (Z(NINC))
END OF SUBROUTINE

Figure 25. Flow chart for subroutine QTFE.

Subroutine LNFIT

This subroutine fits a measured or calculated particle size distribution to a log-normal distribution. A mass median diameter, geometric standard deviation, and fit parameter are determined in order to describe the fitted log-normal distribution. In order to use this subroutine, subroutine CFIT must be supplied.

Using equation (59), we can write the cumulative fraction (S(X)) up to a given particle size for a log-normal distribution in the form

$$S(X) = \int_{-\infty}^{X} f_{L-N}\, dz$$

$$= \frac{1}{\sigma_z \sqrt{2\pi}} \int_{-\infty}^{X} \text{EXP} \left[- \frac{(z-\bar{z})^2}{2\sigma_z^{\,2}} \right] dz \qquad (68)$$

where the symbols are as previously defined. By making a change in variable of the form

$$t = \frac{z-\bar{z}}{\sigma_z} \qquad (69)$$

and

$$dz = \sigma_z\, dt \quad , \qquad (70)$$

we can write equation (68) in the form

$$S(t') = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t'} \text{EXP} \left[- \frac{t^2}{2} \right] dt \quad . \qquad (71)$$

The cumulative fraction (Q(t′)) greater than a given particle size can be expressed in the form

$$Q(t') = \frac{1}{\sqrt{2\pi}} \int_{t'(Q)}^{\infty} \text{EXP} \left[- \frac{t^2}{2} \right] dt \quad . \qquad (72)$$

S(t′) and Q(t′) are called inverse Gaussian (Normal) integrals.

The variable t′(Q) can be approximated by the expression[38]

$$t'(Q) = \phi - \left\{\frac{a_0 + a_1\phi + a_2\,\phi^2}{1 + b_1\,\phi + b_2\,\phi^2 + b_3\,\phi^3}\right\} \quad , \qquad (73)$$

where the error in $t'(Q)$ is equal to or less than 0.00045 and $a_0 = 2.515517$, $a_1 = 0.802853$, $a_2 = 0.010328$, $b_1 = 1.432788$, $b_2 = 0.189269$, and $b_3 = 0.001308$. The approximate expression for $t'(Q)$ is valid for $0<Q(t') \leq 0.5$. The variable ϕ is defined as

$$\phi = \sqrt{\ln\left(\frac{1}{Q^2}\right)} \quad . \qquad (74)$$

Since $S(t') + Q(t') = 1$, equation (73) can be used for $t'(S)$ where $0.5 \leq S(t')<1$. In this case,

$$\phi = \sqrt{\ln\left(\frac{1}{1-Q}\right)^2} = \sqrt{\ln\left(\frac{1}{S}\right)^2} \quad . \qquad (75)$$

Due to the symmetry of the Gaussian (Normal) distribution function, $S(-\infty) = 0$, $S(0) = 0.5$, and $S(\infty) = 1.0$. In addition, we may employ the relationship

$$t'(Q = u) = - t'(Q = 1-u) \quad , \qquad (76)$$

where $0 \leq u \leq 1$.

The variable $t'(S)$ which is related to a true log-normal distribution can be determined from equations (73), (75), and (76) for any given cumulative fraction S. Inspection of equations (68), (69), and (71) shows that the variable t' corresponds to the natural logarithm of a quantity which is linearly related to the natural logarithm of a given particle size. In the procedure used to fit the actual cumulative distribution to a log-normal distribution, the value of t' and the natural logarithm of the actual particle size (z') are determined for each actual cumulative fraction S. The set of points (z',t') constitute a function that can be plotted on log-log axes. If the actual distribution is a log-normal distribution,

$$t' = \frac{z'}{\sigma_z} - \frac{\bar{z}'}{\sigma_z} \qquad (77)$$

for all z' and t' and the points (z',t') will lie on a straight line which has a slope of $\frac{1}{\sigma_z}$ and a t'-intercept of $-\frac{\bar{z}'}{\sigma_z}$. The points (z',t') are fitted to a straight line of the form

$$t' = A + Bz' \tag{78}$$

by calling subroutine CFIT which uses a linear least squares fit procedure.

Since $t' = 0$ at the point where 50% of the distribution has been accumulated, the fitted, actual d_{50} can be obtained from

$$0 = A + Bz' = A + B \ln d_{50} \quad . \tag{79}$$

Thus,

$$d_{50} = \mathrm{EXP}\ (- A/B) \quad . \tag{80}$$

In order to obtain the geometric standard deviation (σ_p) of the fitted log-normal distribution, it is recognized from equations (77), (78), and (80) that

$$A = - \frac{\bar{z}}{\sigma_z} = - \frac{\ln d_{50}}{\sigma_z} = \frac{A}{B \ln \sigma_p} \tag{81}$$

or

$$\sigma_p = \mathrm{EXP}\ (1/B) \quad . \tag{82}$$

Figure 26 shows a detailed flow chart for this subroutine. This subroutine is called by the main program and subroutine ADJUST. Information which is transmitted to and from this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

PRCU(I) - Measured or known cumulative mass fractions.

D50 - Mass median diameter obtained from the fit of the actual distribution to a log-normal distribution (μm).

SIGMAP - Geometric standard deviation obtained from the fit of the actual distribution to a log-normal distribution.

GFIT - Goodness of fit parameter for the log-normal fit.

The following is a list of the necessary variables which are in common with the main program and subroutine ADJUST.

ENDPT(I) - Particle diameters corresponding to the measured or known cumulative mass fractions (μm).

NENDPT - Number of points in the measured or known distribution.

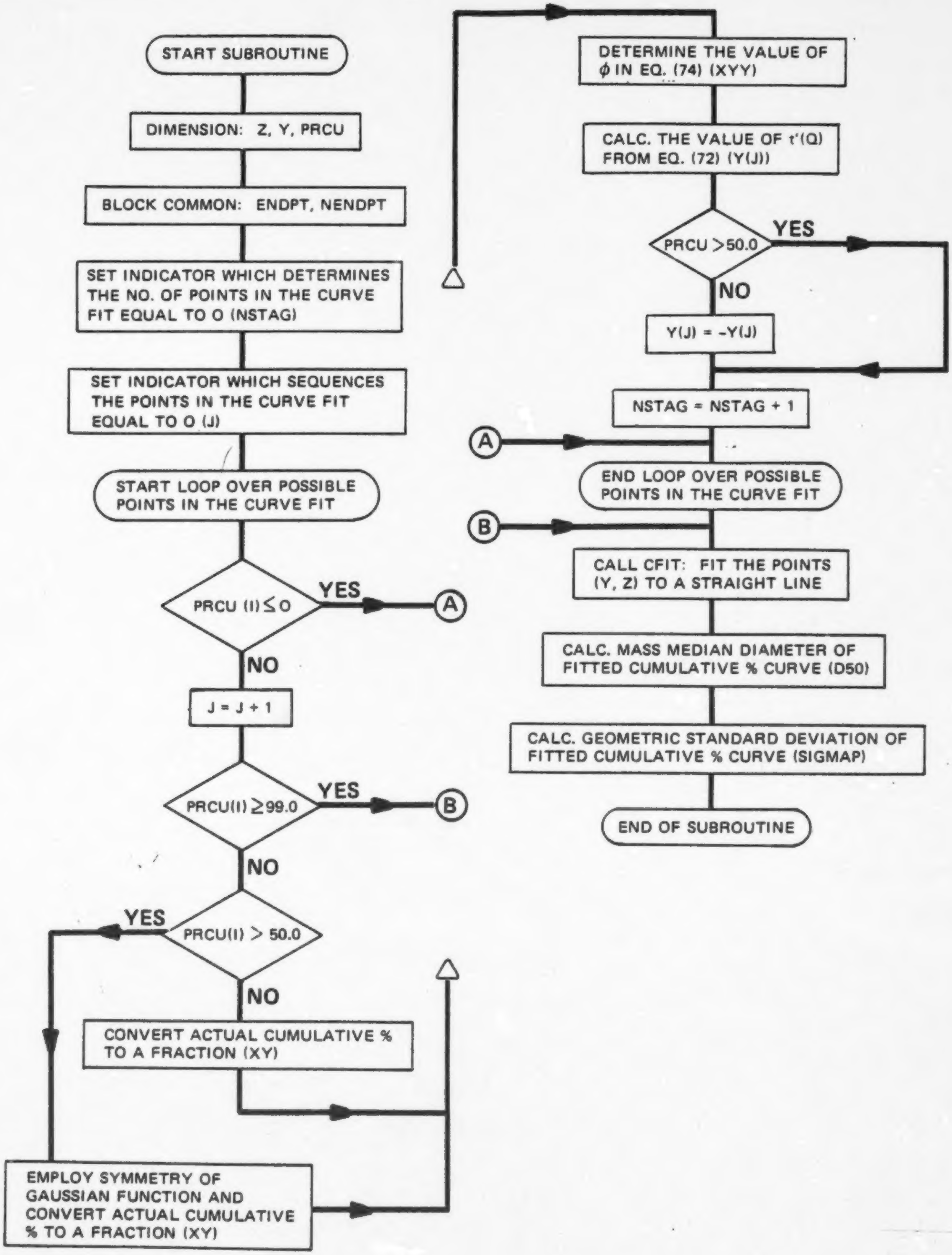

START SUBROUTINE
DIMENSION: Z, Y, PRCU
BLOCK COMMON: ENDPT, NENDPT
SET INDICATOR WHICH DETERMINES THE NO. OF POINTS IN THE CURVE FIT EQUAL TO O (NSTAG)
SET INDICATOR WHICH SEQUENCES THE POINTS IN THE CURVE FIT EQUAL TO O (J)
START LOOP OVER POSSIBLE POINTS IN THE CURVE FIT
PRCU (I) ≤ O
YES
A
NO
J = J + 1
PRCU(I) ≥ 99.0
YES
B
NO
PRCU(I) > 50.0
YES
NO
CONVERT ACTUAL CUMULATIVE % TO A FRACTION (XY)
EMPLOY SYMMETRY OF GAUSSIAN FUNCTION AND CONVERT ACTUAL CUMULATIVE % TO A FRACTION (XY)
DETERMINE THE VALUE OF φ IN EQ. (74) (XYY)
CALC. THE VALUE OF t'(Q) FROM EQ. (72) (Y(J))
PRCU > 50.0
YES
NO
Y(J) = -Y(J)
NSTAG = NSTAG + 1
A
END LOOP OVER POSSIBLE POINTS IN THE CURVE FIT
B
CALL CFIT: FIT THE POINTS (Y, Z) TO A STRAIGHT LINE
CALC. MASS MEDIAN DIAMETER OF FITTED CUMULATIVE % CURVE (D50)
CALC. GEOMETRIC STANDARD DEVIATION OF FITTED CUMULATIVE % CURVE (SIGMAP)
END OF SUBROUTINE

Figure 26. Flow chart for subroutine LNFIT.

Of the above variables, the values of PRCU, ENDPT, and NENDPT must be supplied by the calling program. D50, SIGMAP, and GFIT are determined in the subroutine. I can not exceed a value of 21. The restriction on I limits the number of particle diameters in the particle size distribution.

In the calculations, all points which have an actual cumulative fraction of zero are ignored. Since measured cumulative particle size distributions may tend to flatten out for the larger particle sizes, the calculation is cut off at the point where 99% of the distribution is accumulated. This is done in order to keep the curve fit from being prejudiced towards the flat portion of the curve even though the majority of the distribution is log-normal. The cumulative fractions and corresponding particle diameters should be stored in arrays PRCU and ENDPT, respectively, in order from smallest to largest values. If the goodness of fit parameter GFIT, which is determined in subroutine CFIT, is nearly 1, the actual distribution is very close to a log-normal distribution and the fitted d_{50} and σ_p are meaningful quantities. If GFIT is much less than 1, the actual distribution should be examined in order to determine if the fitted d_{50} and σ_p are meaningful quantities.

Subroutine CFIT

This subroutine fits a set of data points to a straight line by using a least squares fit procedure.[39] If the data points (x,y) are to be fitted to a linear relationship of the form

$$y = a + bx \quad , \tag{83}$$

the problem is to find the undetermined coefficients a and b such that the line is a good fit to the data. In this case, application of the principle of least squares results in two normal equations of the form

$$ma + \sum x_j b = \sum y_j \tag{84}$$

and

$$\sum x_j a + \sum x_j^2 b = \sum x_j y_j \quad , \tag{85}$$

where (x_j, y_j) are the data points and m is the number of data points. Equations (84) and (85) form a system of two simultaneous equations in two unknowns. The solutions of this system of equations are

$$a = \frac{1}{\Delta} \left[\left(\sum y_j\right) \left(\sum x_j^2\right) - \left(\sum x_j y_j\right) \left(\sum x_j\right) \right] \qquad (86)$$

and

$$b = \frac{1}{\Delta} \left[m \left(\sum x_j y_j\right) - \left(\sum y_j\right) \left(\sum x_j\right) \right] , \qquad (87)$$

where

$$\Delta = m \left(\sum x_j^2\right) - \left(\sum x_j\right)^2 \quad . \qquad (88)$$

With the above determination of a and b, the least squares fit to the data is obtained.

A linear-correlation coefficient r can be constructed in order to measure the degree of linear correlation or the probability that a linear relationship exists between the two observed variables x and y. Since we are interested in the interrelationship between the variables x and y, we can equally well consider x as a function of y and ask if the data correspond to a straight line of the form

$$x = a' + b' y \quad . \qquad (89)$$

The values of the coefficients a′ and b′ will be different from those of a and b in equation (83), but they are related if the variables x and y are correlated.

The inverse slope b′ is determined in the same manner as b

$$b' = \frac{1}{\Delta'} \left[m \left(\sum x_j y_j\right) - \left(\sum y_j\right) \left(\sum x_j\right) \right] \qquad (90)$$

where

$$\Delta' = m \left(\sum y_j^2\right) - \left(\sum y_j\right)^2 \quad . \qquad (91)$$

If there is no correlation between the variables x and y, the least-squares fit must yield a horizontal straight line and $b = b' = 0$.

If there is complete correlation between x and y, there exists a relationship between the coefficients a and b of equation (83) and the coefficients a′ and b′ of equation (89). From equations (83) and (89),

$$y = -\frac{a'}{b'} + \frac{1}{b'}x = a + bx \quad . \tag{92}$$

Equating coefficients gives

$$a = -\frac{a}{b} \tag{93}$$

and

$$b = \frac{1}{b'} \quad . \tag{94}$$

If there is complete correlation, we see that $bb' = 1$. If there is no correlation, both b and b' are 0. Thus, the quantity

$$r = \sqrt{bb'} \tag{95}$$

is defined as the linear-correlation coefficient and is used as a measure of the degree of linear correlation. The value of r ranges from 0, when there is no correlation, to 1, when there is complete correlation.

In the context of the model of electrostatic precipitation, r is called the goodness of fit parameter. If r is much less than 1, the coefficients a and b, which are also used in subroutine LNFIT, may not lead to meaningful information for the user.

This subroutine is called by subroutine LNFIT. Figure 27 shows a detailed flow chart for this subroutine. All information which is transmitted between subroutine LNFIT and this subroutine is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

A - Constant term in the fitted linear relationship.

B - Coefficient of the independent variable in the fitted linear relationship.

R - Linear correlation coefficient (goodness of fit parameter).

NSTAG - Number of data points.

Z(I) - Measured or known values of the independent variable.

Y(I) - Measured or known values of the dependent variable.

Of the above variables, the values of NSTAG, Z, and Y must be provided by the calling program (subroutine LNFIT). The values

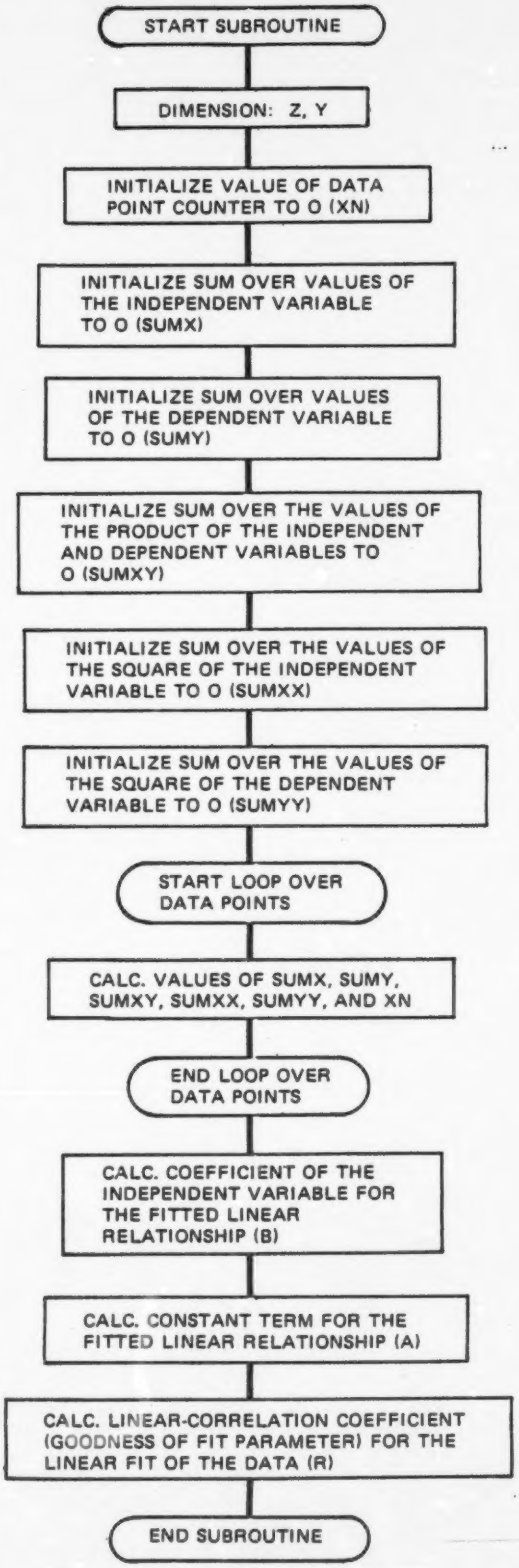

START SUBROUTINE
DIMENSION: Z, Y
INITIALIZE VALUE OF DATA POINT COUNTER TO O (XN)
INITIALIZE SUM OVER VALUES OF THE INDEPENDENT VARIABLE TO O (SUMX)
INITIALIZE SUM OVER VALUES OF THE DEPENDENT VARIABLE TO O (SUMY)
INITIALIZE SUM OVER THE VALUES OF THE PRODUCT OF THE INDEPENDENT AND DEPENDENT VARIABLES TO O (SUMXY)
INITIALIZE SUM OVER THE VALUES OF THE SQUARE OF THE INDEPENDENT VARIABLE TO O (SUMXX)
INITIALIZE SUM OVER THE VALUES OF THE SQUARE OF THE DEPENDENT VARIABLE TO O (SUMYY)
START LOOP OVER DATA POINTS
CALC. VALUES OF SUMX, SUMY, SUMXY, SUMXX, SUMYY, AND XN
END LOOP OVER DATA POINTS
CALC. COEFFICIENT OF THE INDEPENDENT VARIABLE FOR THE FITTED LINEAR RELATIONSHIP (B)
CALC. CONSTANT TERM FOR THE FITTED LINEAR RELATIONSHIP (A)
CALC. LINEAR-CORRELATION COEFFICIENT (GOODNESS OF FIT PARAMETER) FOR THE LINEAR FIT OF THE DATA (R)
END SUBROUTINE

Figure 27. Flow chart for subroutine CFIT.

of A, B, and R are calculated in the subroutine. The index I can not exceed a value of 21. The restriction on I limits the number of particle diameters in the particle size distribution.

Subroutine OPAC

This subroutine calculates and prints differential and total opacity information for the ESP outlet plume. If user supplied indices of refraction are to be used in the calculations, that data is read by this subroutine. Subroutines MASARA, ARAOPT, and MIE are required by OPAC as outlined below.

In order to determine the opacity of a plume, subroutine OPAC calls subroutine MASARA to convert the total and differential masses of particles per cubic meter of effluent gas (M and $\Delta M/\Delta \log D$) to total and differential projected areas (A and $\Delta A/\Delta \log D$). These quantities are then converted to total and differential extinction coefficients (E and $\Delta E/\Delta \log D$) by subroutine ARAOPT, which calls subroutine MIE to calculate the extinction efficiency, Q_{ext}. The value of extinction efficiency normally used for each size band is the average of Q_{ext} at 10 wavelengths weighted according to the photopic color response of the human eye. EPA approved opacity monitors must simulate this color response which is maximum at $\lambda = 0.55$ μm and has a width at half maximum of 0.1 μm. The option to perform the calculations at $\lambda = 0.55$ μm is available to reduce the required computer time. The resulting error depends upon the size distribution. Typical errors found thus far are about 5% in the total extinction coefficient. The extinction efficiency is used by subroutine OPAC to obtain the no-rap, rap, and rap + no-rap plume opacity using equation (26). The optical pathlength L in equation (26) is given by the parameter PATHL read in on the first data card. The opacity calculations can be performed for several refractive indices for each run of the model if desired. The two default values of 1.5-0.0i and 1.5-0.1i will be used if the user does not supply this information. The variation of refractive index with wavelength can be taken into account by the program if these data are available.

In addition to the opacity and total and differential extinction coefficients, the extinction coefficient per unit mass loading, SPE, and the K parameter initiated by Pilat and Ensor[40] are also given. These quantities are related to opacity by

$$\text{Opacity} = 1-\exp(-(SPE)WL) = 1-\exp(-WL/PK), \qquad (96)$$

where

W = outlet particulate mass loading

P = particle density,

and the other quantities are as previously defined.

The information exchange between OPAC and the calling routine (ADJUST or RAPPE) occurs in the calling arguments and in block common statements. The following is a list of the calling arguments with their definitions.

RAPLOS - Mass contained in the outlet emissions due to rapping (mg/DSCM and g/ACM)

YMLLS - Mass leaving the precipitator from adjusted, no-rap calculation (kg/m^3 and g/ACM)

CONVF - Conversion factor for kg/ACM to mg/DSCM

The following is a list of variables, with definitions, which are in common with the calling routine.

DIAM - Particle diameter (m and μm)

NTIMES - Indicator used to avoid repeating many calculations

NCOMPS - Number of compositions (indices of refraction) for which the opacity is to be calculated

NLAMDA - Number of wavelength increments for variable composition

NWAVES - Number of wavelengths at which calculation is to be performed (= 1 or 10)

CMR - Real part of index of refraction

CMI - Imaginary part of index of refraction

UPTOLM - Maximum wavelength in each wavelength band used for variable composition calculations. The minimum wavelength is preset at 400 nm

DD - Mass density of the particles (g/cm^3)

NS - Number of particle size bands

DELTAD - Value of $\Delta\log_{10}$ (Diameter) for each particle size band

DMDLD - Differential mass for the no-rap case (mg/DSCM and g/ACM) changed to normalized differential projected area for the no-rap case in OPAC

RDMDLD - Differential mass for the rapping puff (mg/DSCM and g/ACM) changed to normalized differential projected area for the rapping puff in OPAC

CDMDLD - Differential mass for the rap + no-rap case (mg/DSCM and g/ACM)

PATHL - Pathlength for calculation of opacity (m)

NOPRNT - An indicator used to determine how much opacity information is printed

All of these variables are provided by the calling routine with the exception of CMR, CMI, and UPTOLM if user supplied index of refraction data is read into the program. If this additional data is not read into the program, CMR and CMI are also supplied by the calling routine and UPTOLM is not used. A flow chart for subroutine OPAC is shown in Figure 28.

Subroutine MASARA

This subroutine converts total and differential particle mass per m^3 of gas leaving the ESP to total and normalized differential projected areas of the particles. This is done according to the following equations:

$$A = \frac{3}{2*\text{particle density}} * \sum_j (\Delta M/\Delta \log D)_j / D_j * \Delta \log D_j \tag{97}$$

$$(\Delta A/\Delta \log D)_i = \frac{(\Delta M/\Delta \log D)_i / D_i}{\sum_j (\Delta M/\Delta \log D)_j / D_j * \Delta \log D_j} \tag{98}$$

where D_j is the particle diameter associated with the jth size band, $\Delta M/\Delta \log D$ is the differential particle mass, $\Delta A/\Delta \log D$ is the normalized differential projected area and A is the total projected area of the particles.

A flow chart for subroutine MASARA is shown in Figure 29. The information exchange between subroutine MASARA and subroutine OPAC takes place in the calling argument and requires the following variables:

DENSTY - Particle density (g/cm^3)

NOXES - Number of particle size bands

X - Particle diameter (μm)

FX - Differential mass distribution (g/ACM) and normalized differential projected area distribution

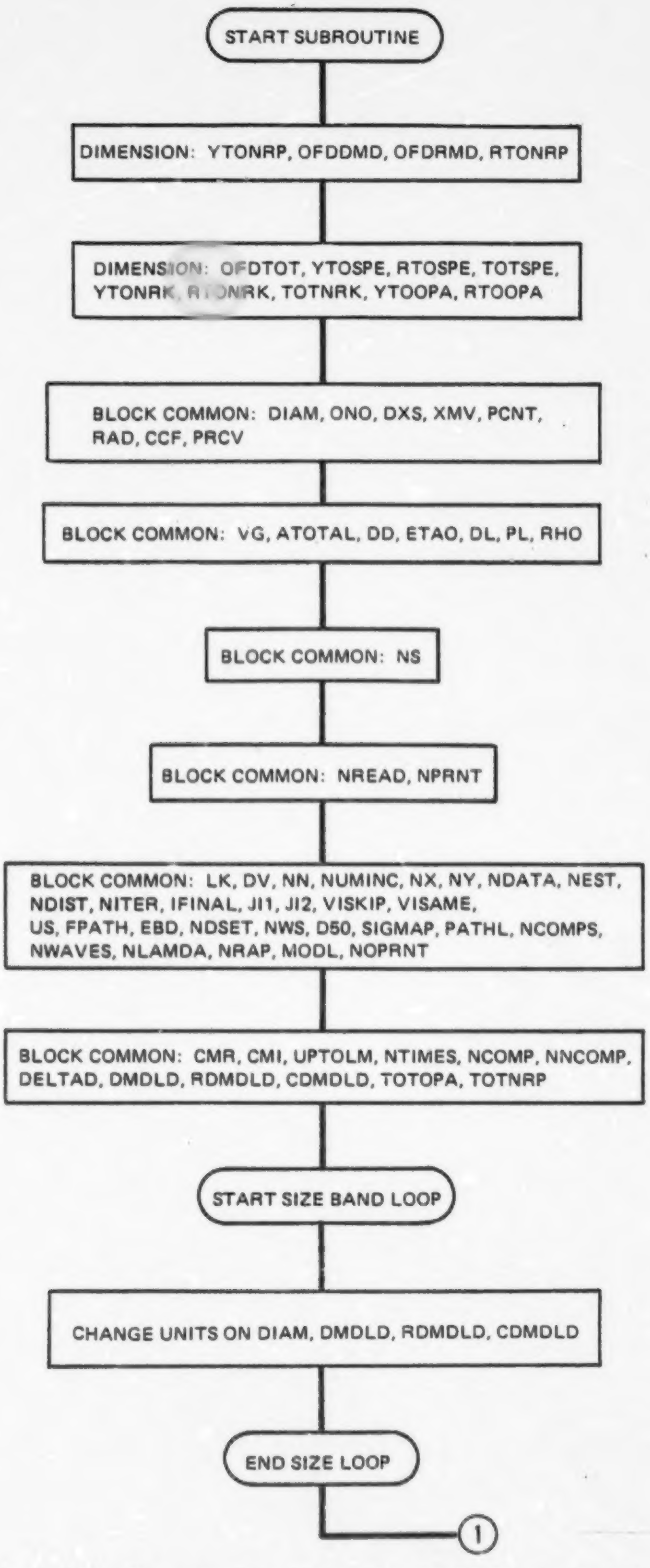

START SUBROUTINE
DIMENSION: YTONRP, OFDDMD, OFDRMD, RTONRP
DIMENSION: OFDTOT, YTOSPE, RTOSPE, TOTSPE, YTONRK, RTONRK, TOTNRK, YTOOPA, RTOOPA
BLOCK COMMON: DIAM, ONO, DXS, XMV, PCNT, RAD, CCF, PRCV
BLOCK COMMON: VG, ATOTAL, DD, ETAO, DL, PL, RHO
BLOCK COMMON: NS
BLOCK COMMON: NREAD, NPRNT
BLOCK COMMON: LK, DV, NN, NUMINC, NX, NY, NDATA, NEST, NDIST, NITER, IFINAL, JI1, JI2, VISKIP, VISAME, US, FPATH, EBD, NDSET, NWS, D50, SIGMAP, PATHL, NCOMPS, NWAVES, NLAMDA, NRAP, MODL, NOPRNT
BLOCK COMMON: CMR, CMI, UPTOLM, NTIMES, NCOMP, NNCOMP, DELTAD, DMDLD, RDMDLD, CDMDLD, TOTOPA, TOTNRP
START SIZE BAND LOOP
CHANGE UNITS ON DIAM, DMDLD, RDMDLD, CDMDLD
END SIZE LOOP
①

Figure 28. Flow chart for subroutine OPAC (Sheet 1 of 9).

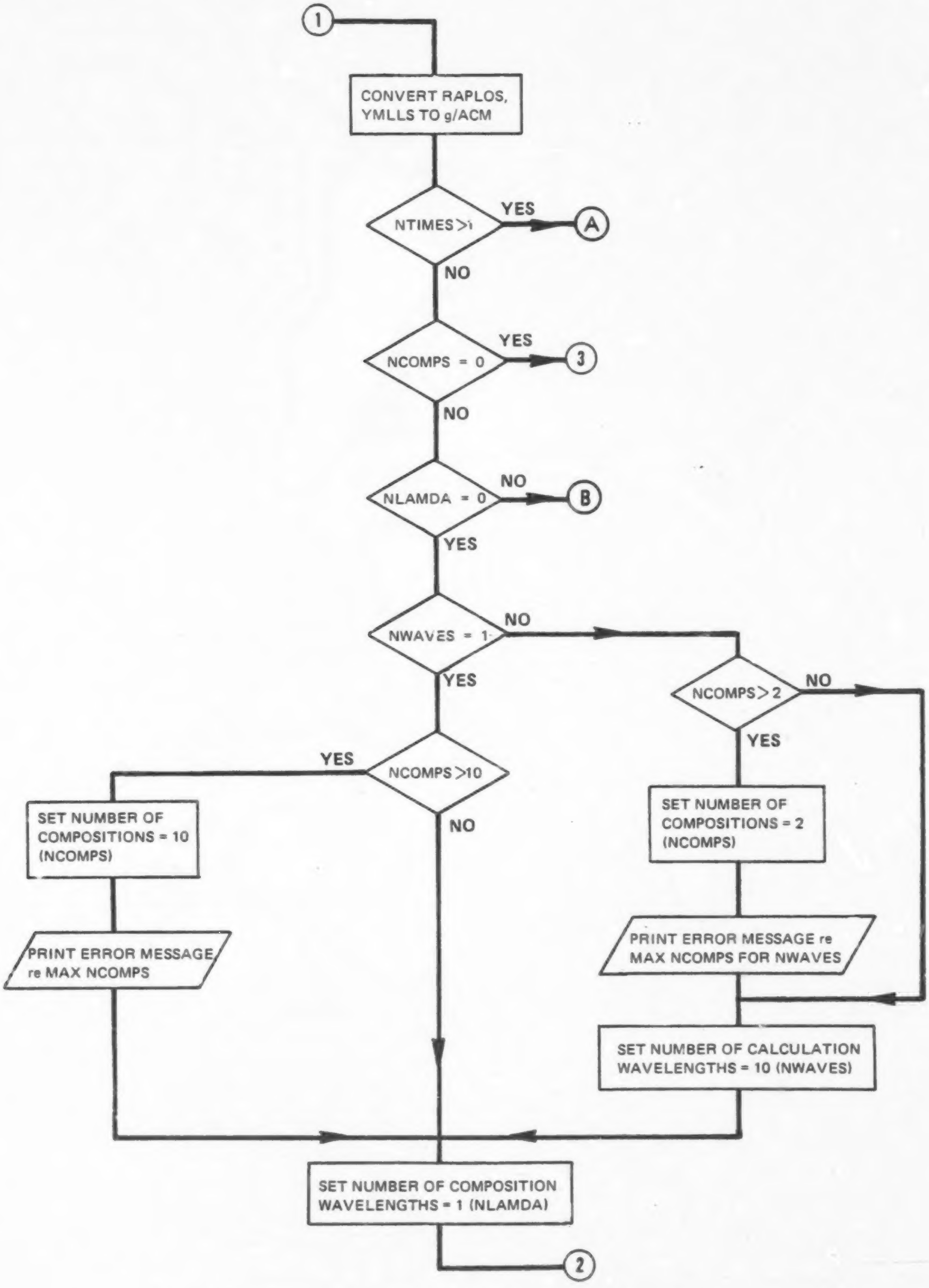

1
CONVERT RAPLOS, YMLLS TO g/ACM
NTIMES>1
YES
A
NO
NCOMPS = 0
YES
3
NO
NLAMDA = 0
NO
B
YES
NWAVES = 1
NO
NCOMPS>2
NO
YES
NCOMPS>10
YES
SET NUMBER OF COMPOSITIONS = 10 (NCOMPS)
NO
SET NUMBER OF COMPOSITIONS = 2 (NCOMPS)
PRINT ERROR MESSAGE re MAX NCOMPS
PRINT ERROR MESSAGE re MAX NCOMPS FOR NWAVES
SET NUMBER OF CALCULATION WAVELENGTHS = 10 (NWAVES)
SET NUMBER OF COMPOSITION WAVELENGTHS = 1 (NLAMDA)
2

Figure 28. Flow chart for subroutine OPAC (Sheet 2 of 9).

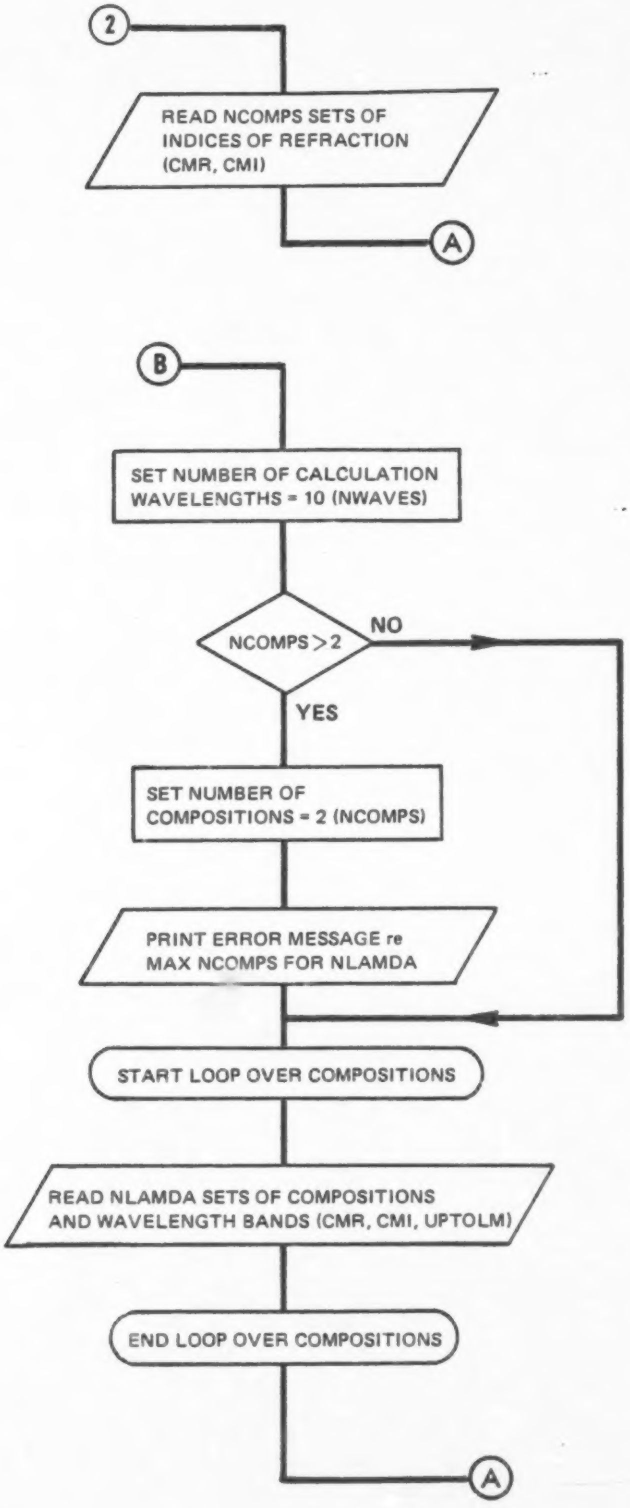

2
READ NCOMPS SETS OF INDICES OF REFRACTION (CMR, CMI)
A
B
SET NUMBER OF CALCULATION WAVELENGTHS = 10 (NWAVES)
NCOMPS > 2
NO
YES
SET NUMBER OF COMPOSITIONS = 2 (NCOMPS)
PRINT ERROR MESSAGE re MAX NCOMPS FOR NLAMDA
START LOOP OVER COMPOSITIONS
READ NLAMDA SETS OF COMPOSITIONS AND WAVELENGTH BANDS (CMR, CMI, UPTOLM)
END LOOP OVER COMPOSITIONS
A

Figure 28. Flow chart for subroutine OPAC (Sheet 3 of 9).

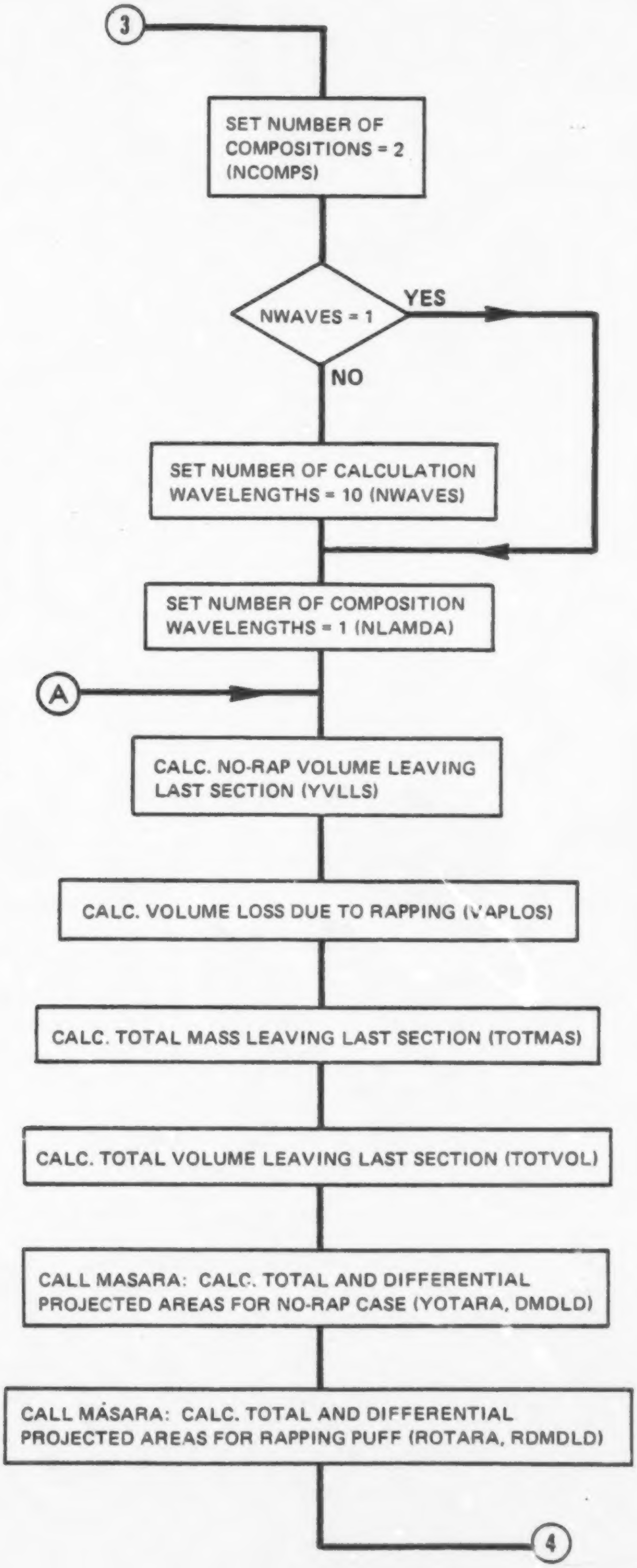

3
SET NUMBER OF COMPOSITIONS = 2 (NCOMPS)
NWAVES = 1
YES
NO
SET NUMBER OF CALCULATION WAVELENGTHS = 10 (NWAVES)
SET NUMBER OF COMPOSITION WAVELENGTHS = 1 (NLAMDA)
A
CALC. NO-RAP VOLUME LEAVING LAST SECTION (YVLLS)
CALC. VOLUME LOSS DUE TO RAPPING (VAPLOS)
CALC. TOTAL MASS LEAVING LAST SECTION (TOTMAS)
CALC. TOTAL VOLUME LEAVING LAST SECTION (TOTVOL)
CALL MASARA: CALC. TOTAL AND DIFFERENTIAL PROJECTED AREAS FOR NO-RAP CASE (YOTARA, DMDLD)
CALL MASARA: CALC. TOTAL AND DIFFERENTIAL PROJECTED AREAS FOR RAPPING PUFF (ROTARA, RDMDLD)
4

Figure 28. Flow chart for subroutine OPAC (Sheet 4 of 9).

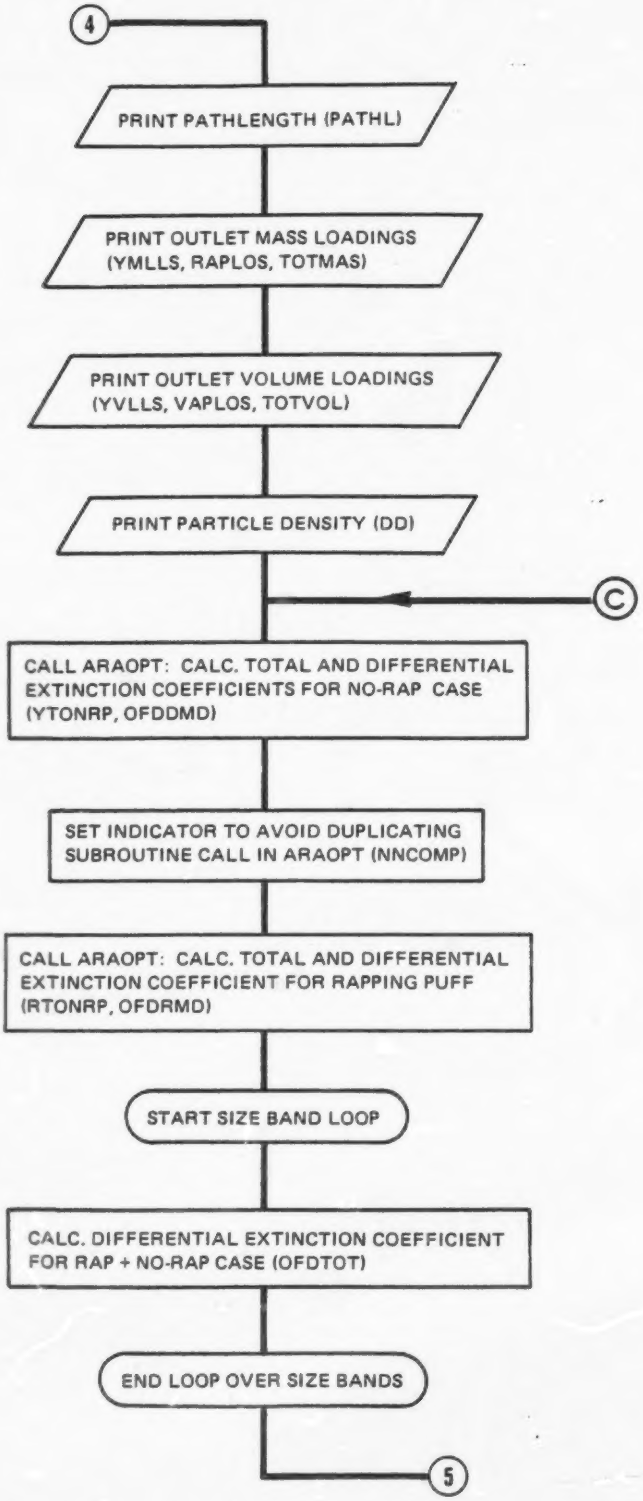

4
PRINT PATHLENGTH (PATHL)
PRINT OUTLET MASS LOADINGS (YMLLS, RAPLOS, TOTMAS)
PRINT OUTLET VOLUME LOADINGS (YVLLS, VAPLOS, TOTVOL)
PRINT PARTICLE DENSITY (DD)
C
CALL ARAOPT: CALC. TOTAL AND DIFFERENTIAL EXTINCTION COEFFICIENTS FOR NO-RAP CASE (YTONRP, OFDDMD)
SET INDICATOR TO AVOID DUPLICATING SUBROUTINE CALL IN ARAOPT (NNCOMP)
CALL ARAOPT: CALC. TOTAL AND DIFFERENTIAL EXTINCTION COEFFICIENT FOR RAPPING PUFF (RTONRP, OFDRMD)
START SIZE BAND LOOP
CALC. DIFFERENTIAL EXTINCTION COEFFICIENT FOR RAP + NO-RAP CASE (OFDTOT)
END LOOP OVER SIZE BANDS
5

Figure 28. Flow chart for subroutine OPAC (Sheet 5 of 9).

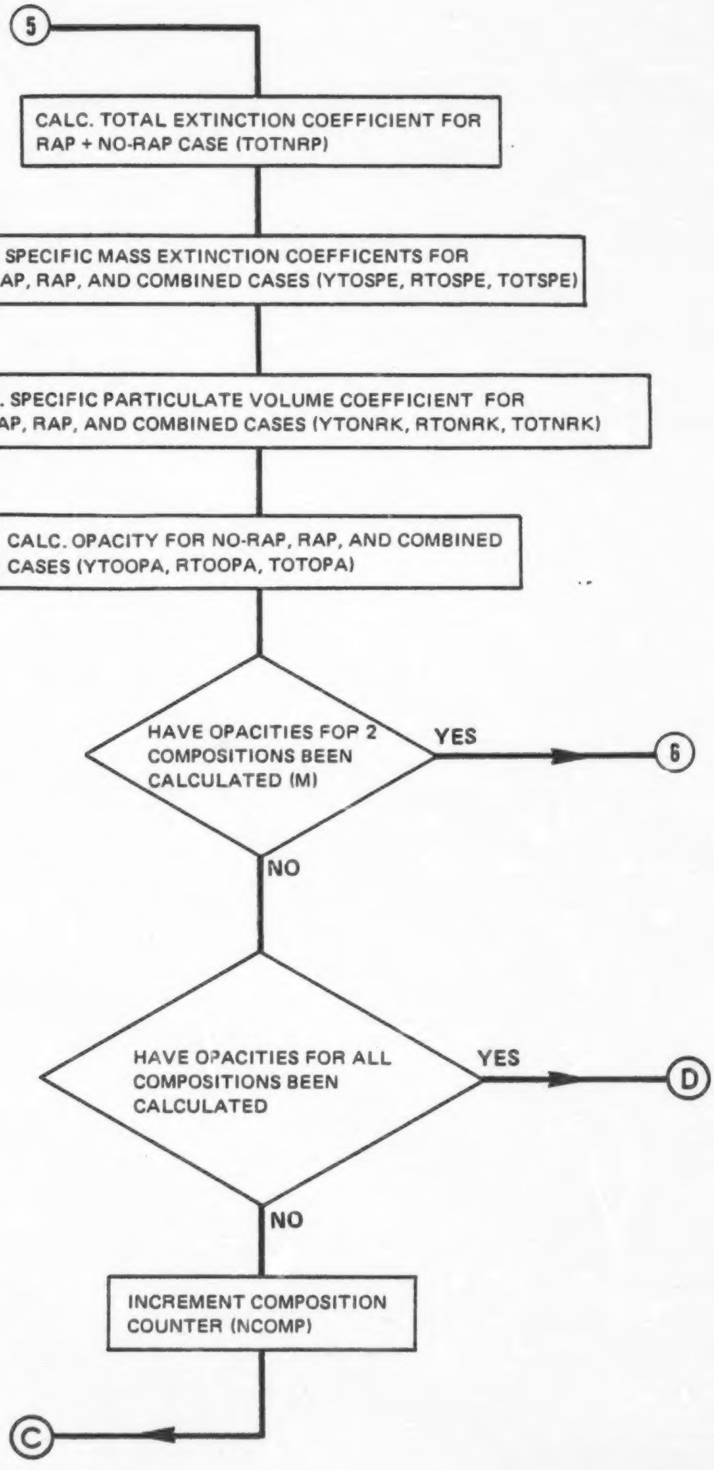
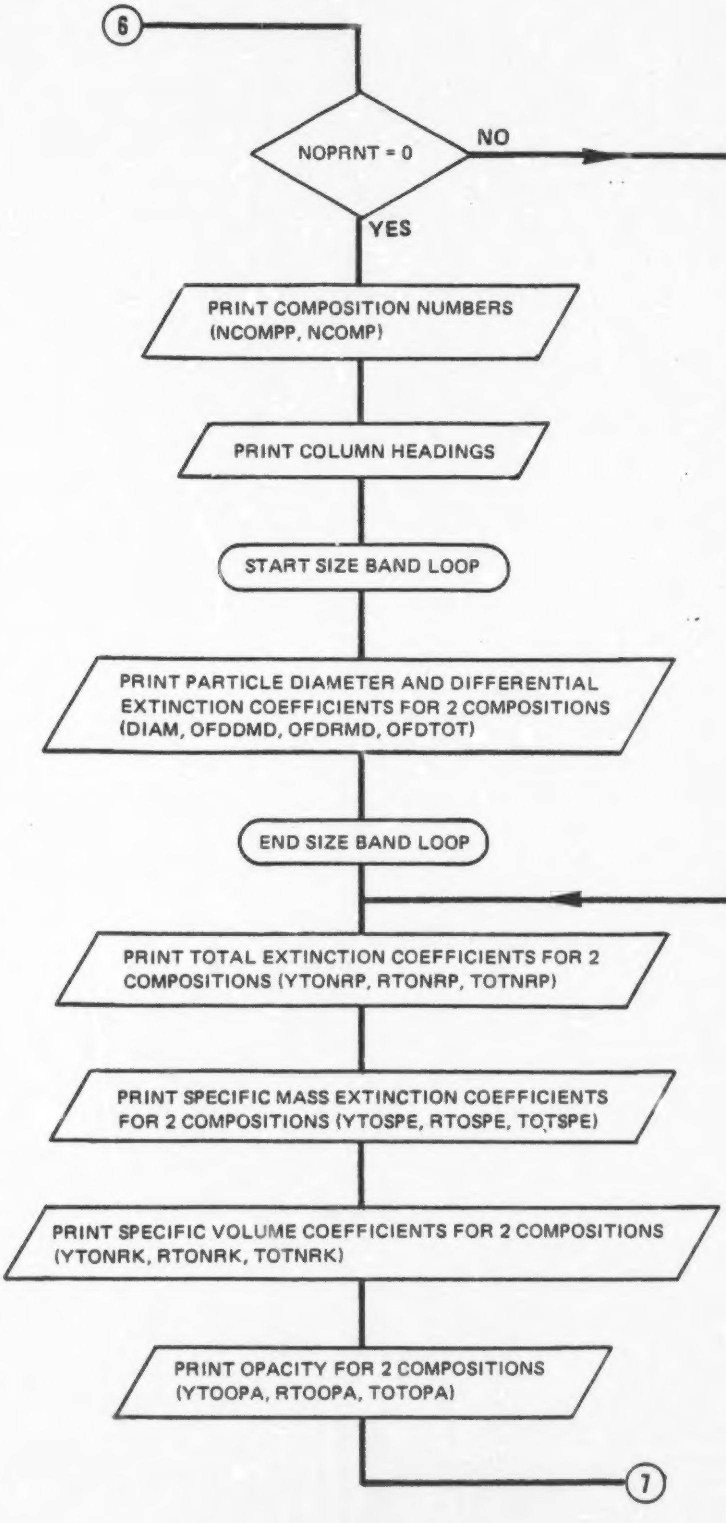

5
CALC. TOTAL EXTINCTION COEFFICIENT FOR RAP + NO-RAP CASE (TOTNRP)
CALC. SPECIFIC MASS EXTINCTION COEFFICENTS FOR NO–RAP, RAP, AND COMBINED CASES (YTOSPE, RTOSPE, TOTSPE)
CALC. SPECIFIC PARTICULATE VOLUME COEFFICIENT FOR NO-RAP, RAP, AND COMBINED CASES (YTONRK, RTONRK, TOTNRK)
CALC. OPACITY FOR NO-RAP, RAP, AND COMBINED CASES (YTOOPA, RTOOPA, TOTOPA)
HAVE OPACITIES FOR 2 COMPOSITIONS BEEN CALCULATED (M)
YES
6
NO
HAVE OPACITIES FOR ALL COMPOSITIONS BEEN CALCULATED
YES
D
NO
INCREMENT COMPOSITION COUNTER (NCOMP)
C

Figure 28. Flow chart for subroutine OPAC (Sheet 6 of 9).



6
NOPRNT = 0
NO
YES
PRINT COMPOSITION NUMBERS (NCOMPP, NCOMP)
PRINT COLUMN HEADINGS
START SIZE BAND LOOP
PRINT PARTICLE DIAMETER AND DIFFERENTIAL EXTINCTION COEFFICIENTS FOR 2 COMPOSITIONS (DIAM, OFDDMD, OFDRMD, OFDTOT)
END SIZE BAND LOOP
PRINT TOTAL EXTINCTION COEFFICIENTS FOR 2 COMPOSITIONS (YTONRP, RTONRP, TOTNRP)
PRINT SPECIFIC MASS EXTINCTION COEFFICIENTS FOR 2 COMPOSITIONS (YTOSPE, RTOSPE, TOTSPE)
PRINT SPECIFIC VOLUME COEFFICIENTS FOR 2 COMPOSITIONS (YTONRK, RTONRK, TOTNRK)
PRINT OPACITY FOR 2 COMPOSITIONS (YTOOPA, RTOOPA, TOTOPA)
7

Figure 28. Flow chart for subroutine OPAC (Sheet 7 of 9).

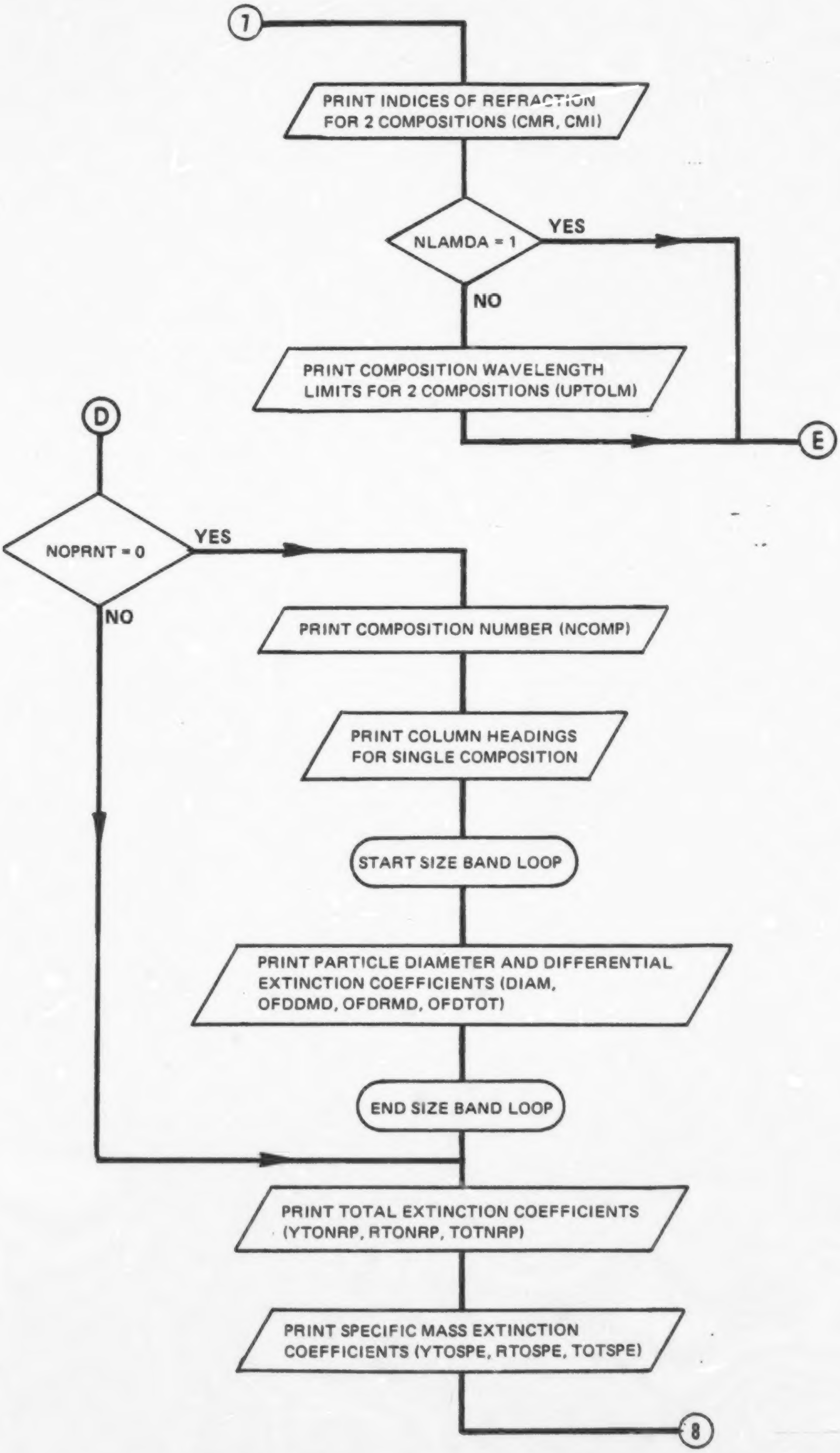

7
PRINT INDICES OF REFRACTION FOR 2 COMPOSITIONS (CMR, CMI)
NLAMDA = 1
YES
NO
PRINT COMPOSITION WAVELENGTH LIMITS FOR 2 COMPOSITIONS (UPTOLM)
E
D
NOPRNT = 0
YES
NO
PRINT COMPOSITION NUMBER (NCOMP)
PRINT COLUMN HEADINGS FOR SINGLE COMPOSITION
START SIZE BAND LOOP
PRINT PARTICLE DIAMETER AND DIFFERENTIAL EXTINCTION COEFFICIENTS (DIAM, OFDDMD, OFDRMD, OFDTOT)
END SIZE BAND LOOP
PRINT TOTAL EXTINCTION COEFFICIENTS (YTONRP, RTONRP, TOTNRP)
PRINT SPECIFIC MASS EXTINCTION COEFFICIENTS (YTOSPE, RTOSPE, TOTSPE)
8

Figure 28. Flow chart for subroutine OPAC (Sheet 8 of 9).

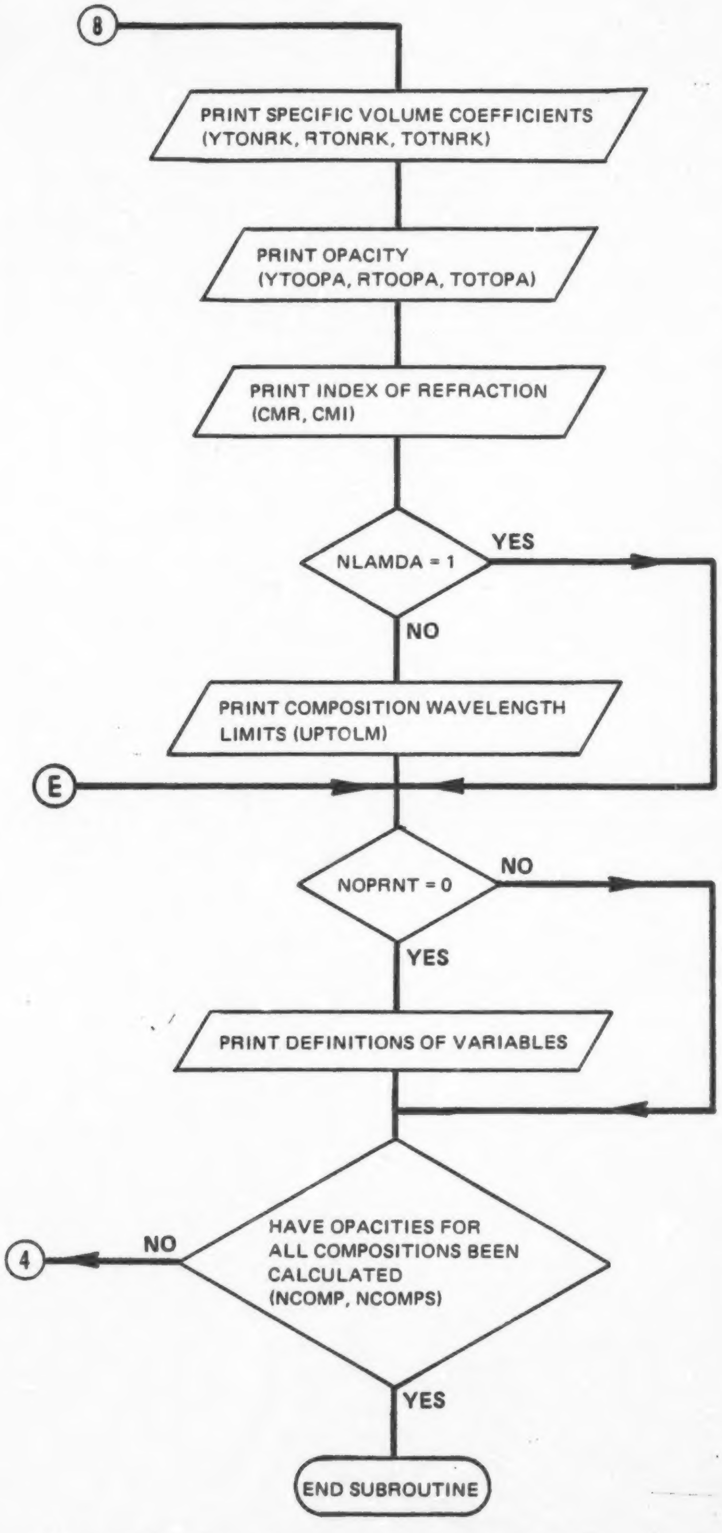

8
PRINT SPECIFIC VOLUME COEFFICIENTS (YTONRK, RTONRK, TOTNRK)
PRINT OPACITY (YTOOPA, RTOOPA, TOTOPA)
PRINT INDEX OF REFRACTION (CMR, CMI)
NLAMDA = 1
YES
NO
PRINT COMPOSITION WAVELENGTH LIMITS (UPTOLM)
E
NOPRNT = 0
NO
YES
PRINT DEFINITIONS OF VARIABLES
HAVE OPACITIES FOR ALL COMPOSITIONS BEEN CALCULATED (NCOMP, NCOMPS)
NO
4
YES
END SUBROUTINE

Figure 28. Flow chart for subroutine OPAC (Sheet 9 of 9).

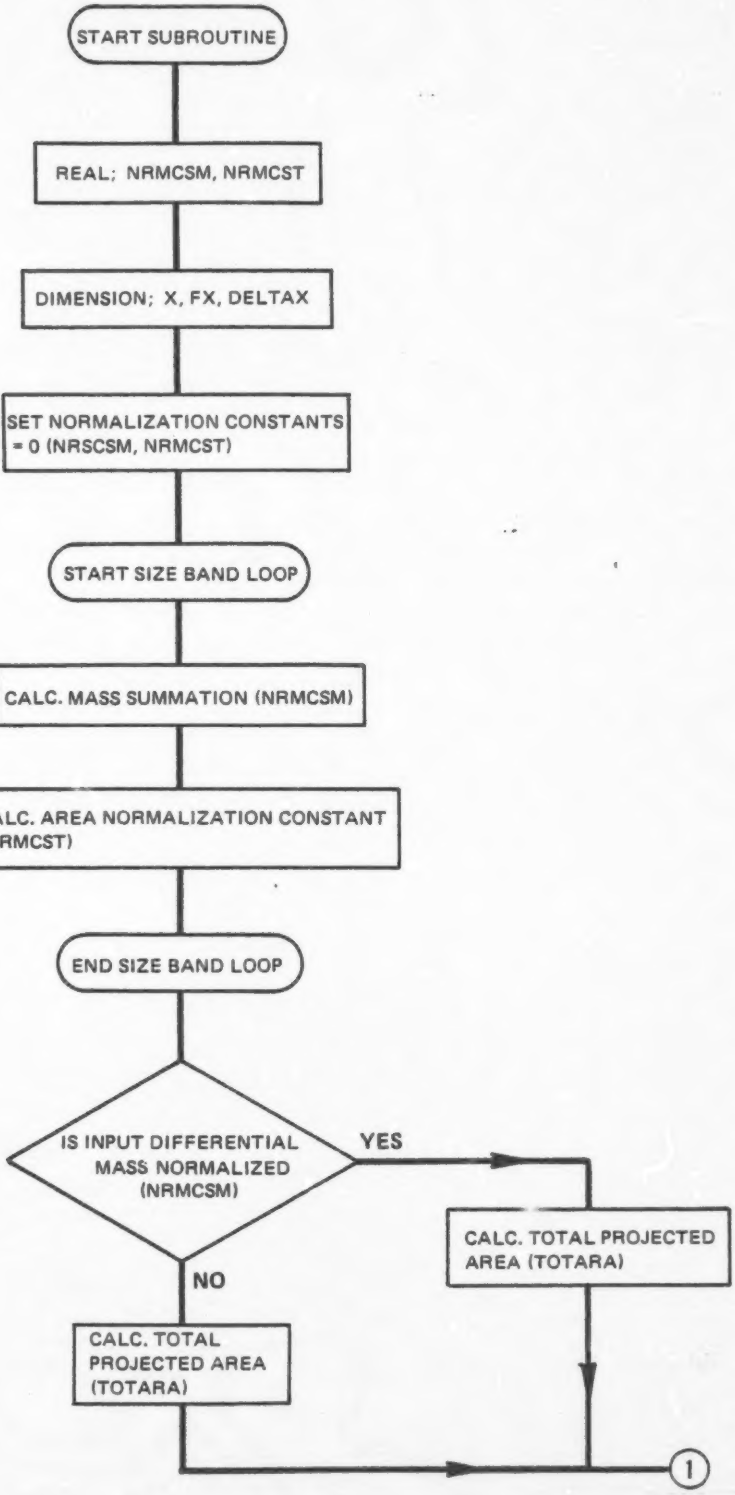

START SUBROUTINE
REAL; NRMCSM, NRMCST
DIMENSION; X, FX, DELTAX
SET NORMALIZATION CONSTANTS = 0 (NRSCSM, NRMCST)
START SIZE BAND LOOP
CALC. MASS SUMMATION (NRMCSM)
CALC. AREA NORMALIZATION CONSTANT (NRMCST)
END SIZE BAND LOOP
IS INPUT DIFFERENTIAL MASS NORMALIZED (NRMCSM)
YES
CALC. TOTAL PROJECTED AREA (TOTARA)
NO
CALC. TOTAL PROJECTED AREA (TOTARA)
1

Figure 29. Flow chart for subroutine MASARA (Sheet 1 of 2).

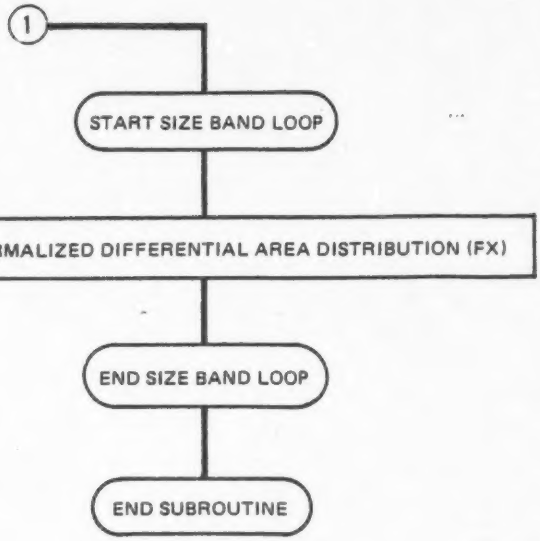

1
START SIZE BAND LOOP
CALC. NORMALIZED DIFFERENTIAL AREA DISTRIBUTION (FX)
END SIZE BAND LOOP
END SUBROUTINE

Figure 29. Flow chart for subroutine MASARA (Sheet 2 of 2).

DELTAX - Value of $\Delta\log_{10}$ (Diameter) for each particle size band

TOTMAS - Total mass leaving the precipitator (g/ACM)

TOTARA - Total projected area of the particles leaving the precipitator (m^2/ACM)

Of these, DENSTY, NOXES, X, FX (the first definition), DELTAX, and TOTMAS are provided by the calling routine. FX (the second definition) and TOTARA are created in subroutine MASARA.

Subroutine ARAOPT

This subroutine uses the normalized differential areas and total projected area of the dust particles generated in subroutine MASARA to determine the differential and total extinction coefficients for the outlet plume. The values of the total and differential extinction coefficients are adjusted to compensate for the photopic response of the human eye and the total extinction coefficient is adjusted for the number of effluent particles in each size band. Subroutine MIE is required by this subroutine.

The calculations performed in Subroutine ARAOPT consist of the following steps:

1. Calculate the size parameter $x = \pi D/\lambda$ for a given value of particle diameter D and wavelength λ,

2. Call subroutine MIE to calculate the extinction efficiency Q for particle size D and wavelength λ,

3. Scale the value of Q according to the photopic response curve and sum the values of Q,

4. Increment the wavelength and return to step 1,

5. Scale the adjusted, summed value of Q calculated in step 3 according to the fraction of the projected area in this size band $(\Delta A/\Delta \log D)_i$ and sum the values of Q,

6. Repeat steps 1 through 5 until Q has been adjusted for all wavelengths in all size bands,

7. Calculate the extinction coefficient E = total projected area * $Q_{effective}$,

8. Calculate the differential extinction coefficient $\Delta E/\Delta \log D$ for each siza band from

$$(\Delta E/\Delta \log D)_i = \text{total projected area} * [(\Delta A/\Delta \log D)_i * Q_i] \, , \tag{99}$$

where $(\Delta A/\Delta \log D)_i$ is the normalized differential area and Q_i is the photo-adjusted value of Q for the i-th size band. A flow chart for subroutine ARAOPT is shown in Figure 30.

The information exchange between subroutine ARAOPT and the calling subroutine, OPAC, takes place through the calling arguments and through common statements. Definitions of the calling arguments are listed below.

NODES - Number of size bands

D - Particle diameter (μm)

FD - Normalized differential area distribution

TOTARA - Total projected area of the effluent particles (m^2/ACM)

TTOPAR - Total extinction coefficient (m^{-1})

OFD - Differential extinction coefficient distribution (m^{-1})

The variables exchanged through common statements are listed below.

NLAMDA - Number of wavelength increments for variable composition

UPTOLM - Maximum wavelength in each wavelength band used with variable composition calculation

NCOMP - Composition counter with maximum value NCOMPS

NTIMES - Indicator used to avoid repeating many calculations

NNCOMP - Indicator used to avoid repeating many calculations

CMR - Real part of index of refraction

CMI - Imaginary part of index of refraction

DELTAD - Value of $\Delta \log_{10}$ (Diameter) in each size band

NWAVES - Number of calculation wavelengths to be used in calculation (= 1 or 10)

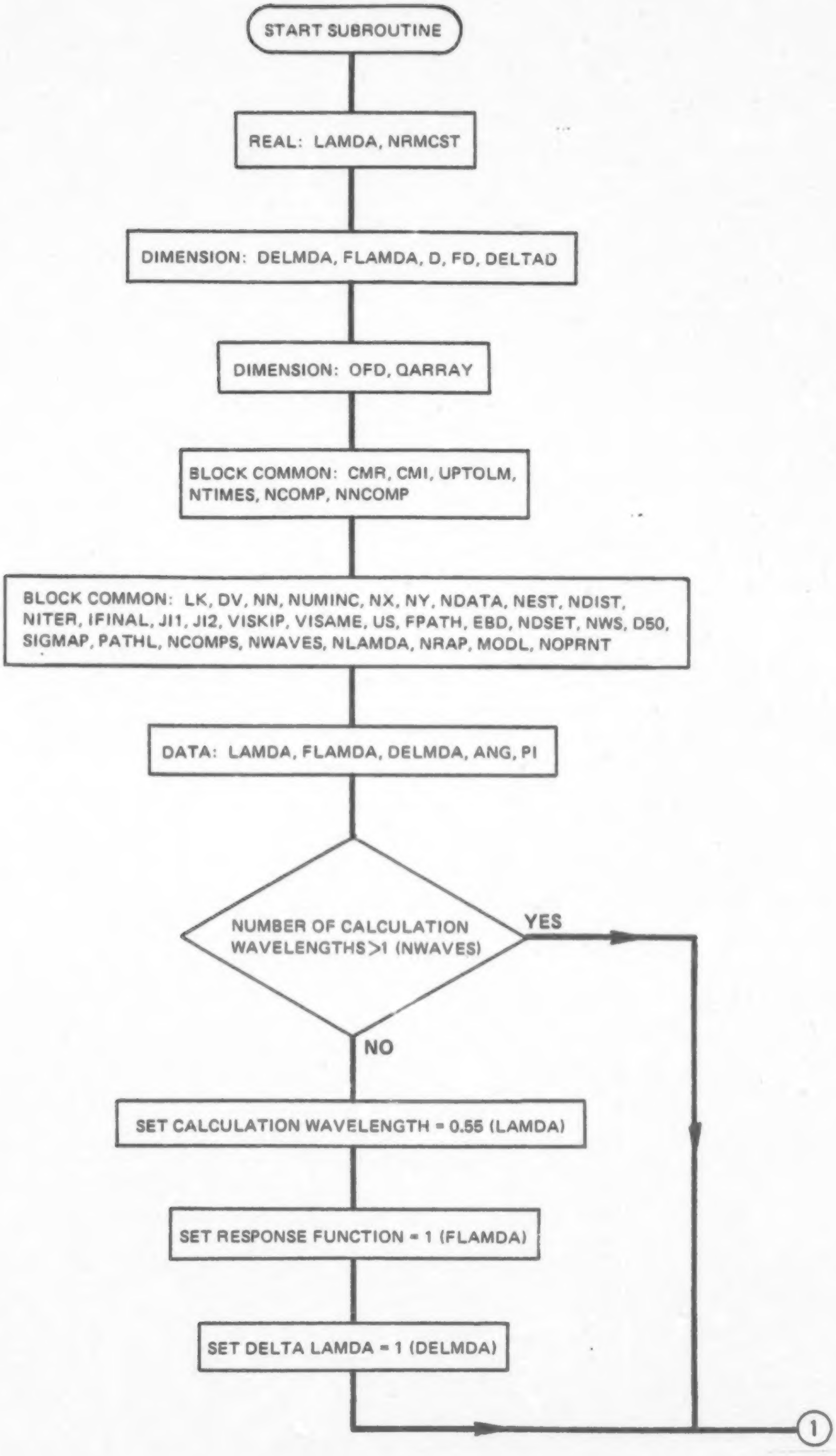

START SUBROUTINE
REAL: LAMDA, NRMCST
DIMENSION: DELMDA, FLAMDA, D, FD, DELTAD
DIMENSION: OFD, QARRAY
BLOCK COMMON: CMR, CMI, UPTOLM, NTIMES, NCOMP, NNCOMP
BLOCK COMMON: LK, DV, NN, NUMINC, NX, NY, NDATA, NEST, NDIST, NITER, IFINAL, JI1, JI2, VISKIP, VISAME, US, FPATH, EBD, NDSET, NWS, D50, SIGMAP, PATHL, NCOMPS, NWAVES, NLAMDA, NRAP, MODL, NOPRNT
DATA: LAMDA, FLAMDA, DELMDA, ANG, PI
NUMBER OF CALCULATION WAVELENGTHS>1 (NWAVES)
YES
NO
SET CALCULATION WAVELENGTH = 0.55 (LAMDA)
SET RESPONSE FUNCTION = 1 (FLAMDA)
SET DELTA LAMDA = 1 (DELMDA)
①

Figure 30. Flow chart for subroutine ARAOPT (Sheet 1 of 3).

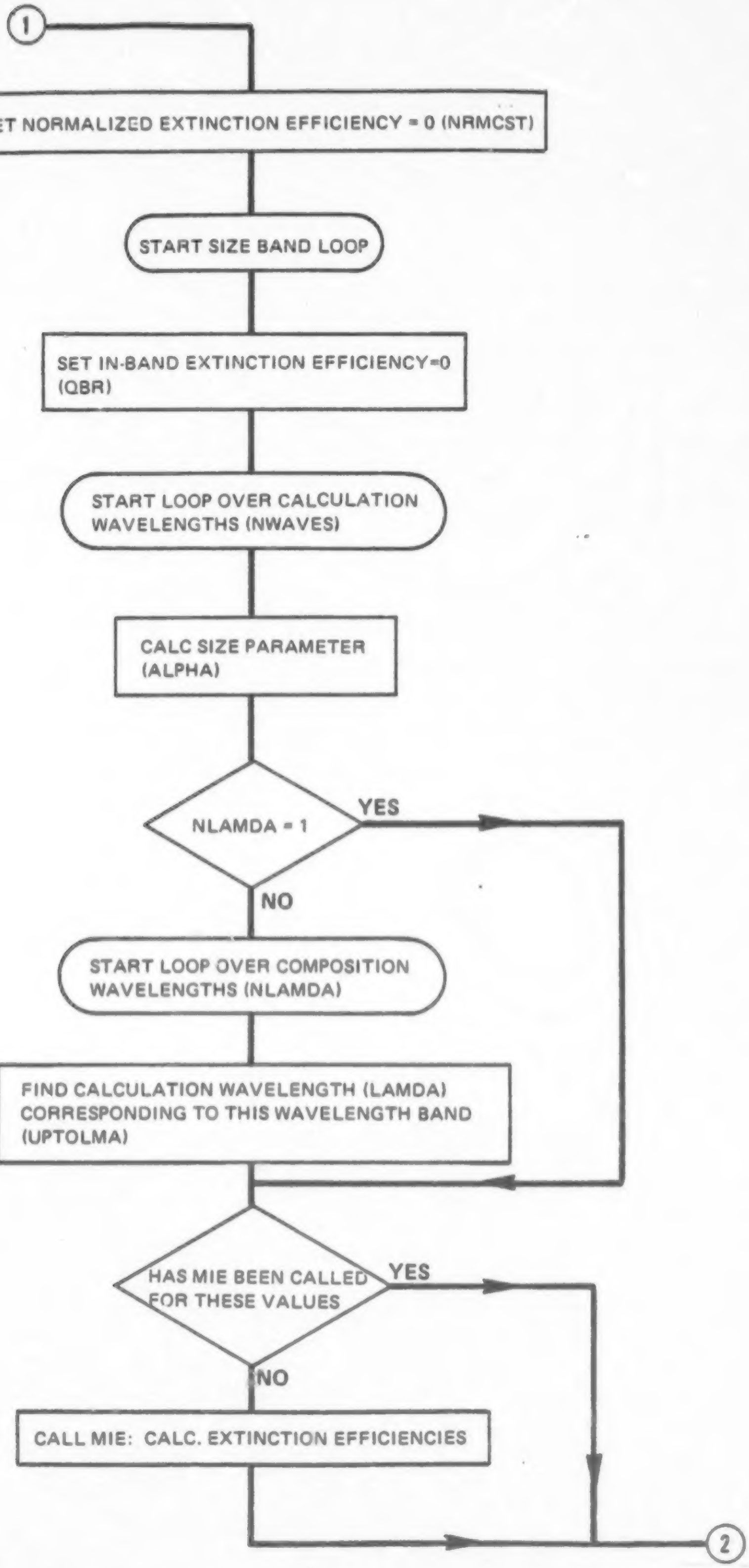

1
SET NORMALIZED EXTINCTION EFFICIENCY = 0 (NRMCST)
START SIZE BAND LOOP
SET IN-BAND EXTINCTION EFFICIENCY=0 (QBR)
START LOOP OVER CALCULATION WAVELENGTHS (NWAVES)
CALC SIZE PARAMETER (ALPHA)
NLAMDA = 1
YES
NO
START LOOP OVER COMPOSITION WAVELENGTHS (NLAMDA)
FIND CALCULATION WAVELENGTH (LAMDA) CORRESPONDING TO THIS WAVELENGTH BAND (UPTOLMA)
HAS MIE BEEN CALLED FOR THESE VALUES
YES
NO
CALL MIE: CALC. EXTINCTION EFFICIENCIES
2

Figure 30. Flow chart for subroutine ARAOPT (Sheet 2 of 3).

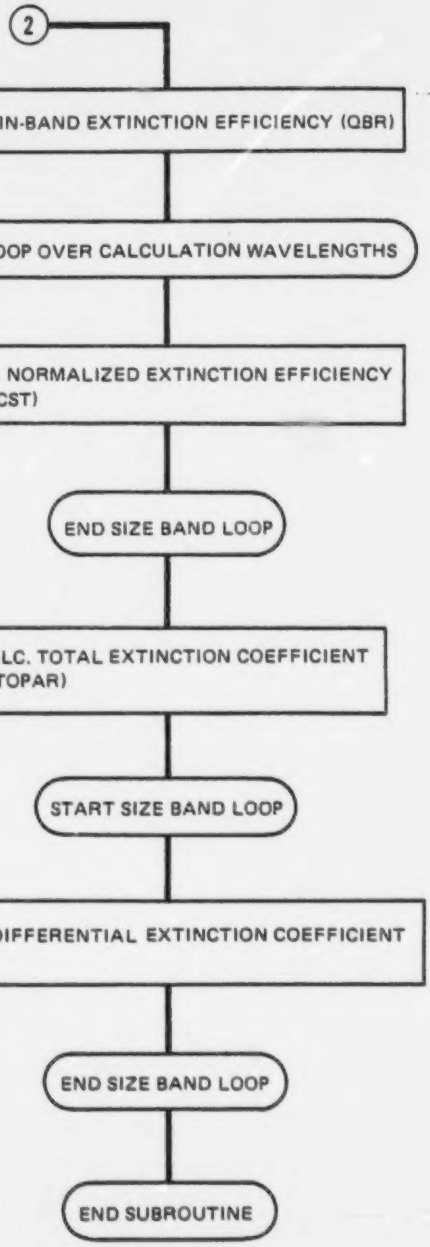

2
CALC IN-BAND EXTINCTION EFFICIENCY (QBR)
END LOOP OVER CALCULATION WAVELENGTHS
CALC. NORMALIZED EXTINCTION EFFICIENCY (NRMCST)
END SIZE BAND LOOP
CALC. TOTAL EXTINCTION COEFFICIENT (TTOPAR)
START SIZE BAND LOOP
CALC. DIFFERENTIAL EXTINCTION COEFFICIENT (OFD)
END SIZE BAND LOOP
END SUBROUTINE

Figure 30. Flow chart for subroutine ARAOPT (Sheet 3 of 3).

Of these, only TTOPAR and OFD are calculated in this subroutine.

Subroutine MIE

This subroutine calculates the extinction efficiency of a spherical particle of diameter D irradiated by light of wavelength λ using Mie's[31] solutions to Maxwell's equations. Following the nomenclature of van de Hulst,[41] the scattering amplitudes perpendicular and parallel to the scattering plane (S_1 and S_2 respectively) can be written in the form

$$S_1(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[a_n \pi_n(\cos\theta) + b_n \tau_n(\cos\theta)\right] \qquad (100)$$

$$S_2(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[b_n \pi_n(\cos\theta) + a_n \tau_n(\cos\theta)\right] \qquad (101)$$

where θ is the scattering angle and π_n and τ_n are defined in terms of the n-th degree first order associated Legendre polynomials $P_n^1(\cos\theta)$ by

$$\pi_n(\cos\theta) = \frac{1}{\sin\theta} P_n^1 (\cos\theta) \qquad (102)$$

and

$$\tau_n(\cos\theta) = \frac{d}{d\theta} P_n^1 (\cos\theta) \ . \qquad (103)$$

The Mie coefficients a_n and b_n from equations (100) and (101) are given by

$$a_n = \frac{\psi'_n(mx)\psi_n(x) - m\psi_n(mx)\psi'_n(x)}{\psi'_n(mx)\zeta_n(x) - m\psi_n(mx)\zeta'_n(x)} \qquad (104)$$

and

$$b_n = \frac{m\psi'_n(mx)\psi_n(x) - \psi_n(mx)\psi'_n(x)}{m\psi'_n(mx)\zeta_n(x) - \psi_n(mx)\zeta'_n(x)} \ , \qquad (105)$$

where x is the size parameter given by

$$x = \frac{\pi D}{\lambda} \ , \qquad (106)$$

and m is the complex index of refraction. The ψ_n and ζ_n are Ricatti-Bessel functions defined by

$$\psi_n(z) = (\pi z/2)^{\frac{1}{2}} J_{n+\frac{1}{2}}(z) , \tag{107}$$

and

$$\zeta_n(z) = (\pi z/2)^{\frac{1}{2}} H^{(2)}_{n+\frac{1}{2}}(z) \tag{108}$$

where $J_{n+\frac{1}{2}}(z)$ is a half order Bessel function and $H^{(2)}_{n+\frac{1}{2}}$ is a Hankel function of the second kind.

In addition to the scattering amplitudes, the extinction efficiency and scattering efficiency can be defined by the Mie coefficients as

$$Q_{ext} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1) \; \mathrm{Re} \; (a_n + b_n) \tag{109}$$

and

$$Q_{sca} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1) \; (|a_n|^2 + |b_n|^2) \; . \tag{110}$$

The absorption efficiency is $Q_{ext} - Q_{sca}$.

In subroutine MIE, the summations in equations (100), (101), (109), and (110) are calculated until Deirmendjian's criteria[43], which states that sufficient accuracy in the summations over n has been achieved when either

$$\frac{|a_n|^2 + |b_n|^2}{n} < 10^{-14} \quad \text{or} \quad n = 1.2\; x + 9 \; ,$$

is satisfied. The computer code used is based on that of Moore.[42] A flow chart of subroutine MIE is shown in Figure 31.

The information exchange between subroutine MIE and the calling subroutine, ARAOPT, takes place through the calling arguments, which are defined in the following list.

C1 - Real part of complex index of refraction

C4 - Imaginary part of complex index of refraction

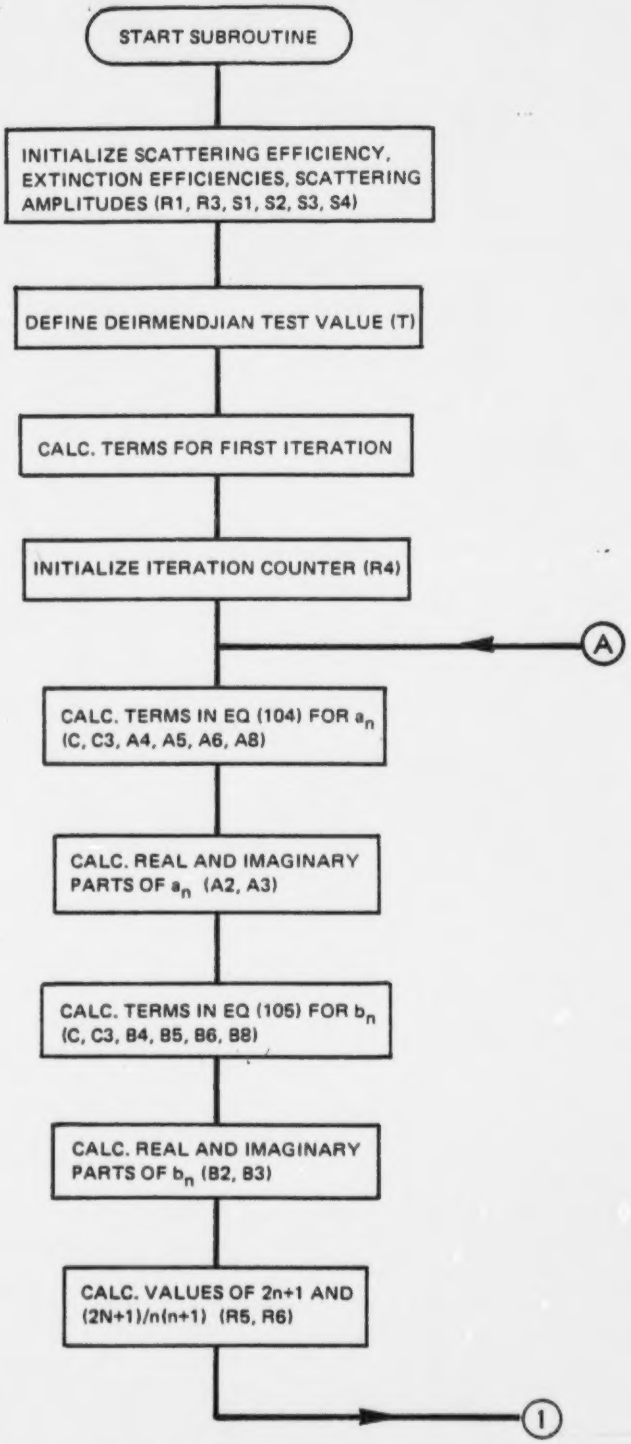

START SUBROUTINE
INITIALIZE SCATTERING EFFICIENCY, EXTINCTION EFFICIENCIES, SCATTERING AMPLITUDES (R1, R3, S1, S2, S3, S4)
DEFINE DEIRMENDJIAN TEST VALUE (T)
CALC. TERMS FOR FIRST ITERATION
INITIALIZE ITERATION COUNTER (R4)
A
CALC. TERMS IN EQ (104) FOR a_n (C, C3, A4, A5, A6, A8)
CALC. REAL AND IMAGINARY PARTS OF a_n (A2, A3)
CALC. TERMS IN EQ (105) FOR b_n (C, C3, B4, B5, B6, B8)
CALC. REAL AND IMAGINARY PARTS OF b_n (B2, B3)
CALC. VALUES OF 2n+1 AND (2N+1)/n(n+1) (R5, R6)
1

Figure 31. Flow chart for subroutine MIE (Sheet 1 of 3).

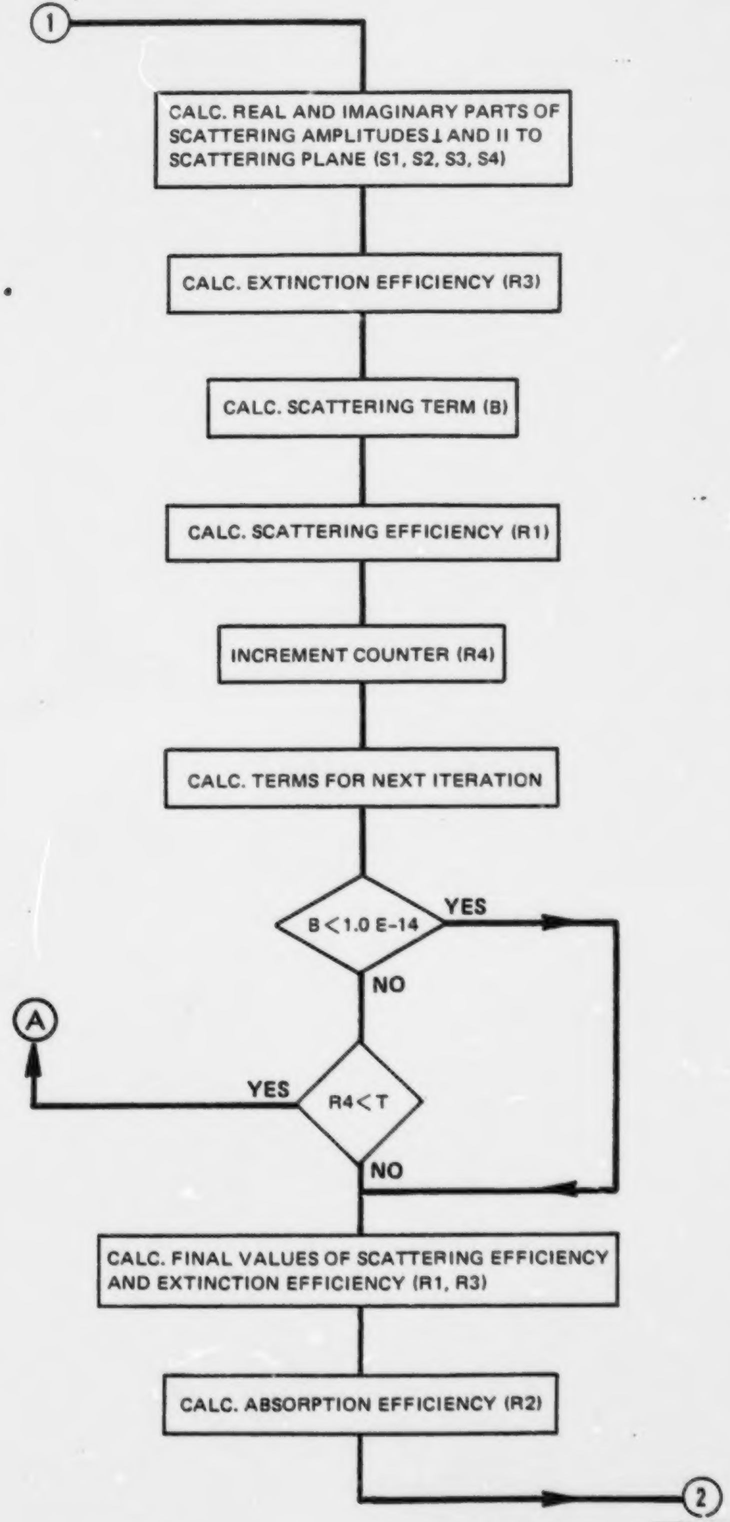

1
CALC. REAL AND IMAGINARY PARTS OF SCATTERING AMPLITUDES ⊥ AND II TO SCATTERING PLANE (S1, S2, S3, S4)
CALC. EXTINCTION EFFICIENCY (R3)
CALC. SCATTERING TERM (B)
CALC. SCATTERING EFFICIENCY (R1)
INCREMENT COUNTER (R4)
CALC. TERMS FOR NEXT ITERATION
B < 1.0 E-14
YES
NO
A
YES
R4 < T
NO
CALC. FINAL VALUES OF SCATTERING EFFICIENCY AND EXTINCTION EFFICIENCY (R1, R3)
CALC. ABSORPTION EFFICIENCY (R2)
2

Figure 31. Flow chart for subroutine MIE (Sheet 2 of 3).

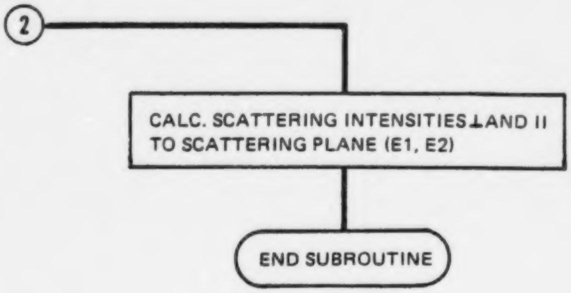

2
CALC. SCATTERING INTENSITIES ⊥ AND II TO SCATTERING PLANE (E1, E2)
END SUBROUTINE

Figure 31. Flow chart for subroutine MIE (Sheet 3 of 3).

X - Size parameter = π*DIAMETER/WAVELENGTH

A1 - Angle of scattering

E1 - Scattering intensity perpendicular to scattering plane

E2 - Scattering intensity parallel to scattering plane

R1 - Scattering efficiency

R2 - Absorption efficiency

R3 - Extinction efficiency

Of these variables, C1, C4, X, and A1 are calculated in the calling routine. E1, E2, R1, R2, and R3 are calculated in subroutine MIE.

Subroutine RAPPE

This subroutine performs the following operations: (1) nonideal adjustments to the ideal efficiency calculation, (2) calculation of the thickness of the collected dust layer as a function of time, (3) calculation of the reentrained particle statistics for inclusion in subsequent ideal efficiency calculations, and (4) calculation and printing of the outlet particle statistics. After these tasks have been accomplished, control of the program is returned to the main routine, where the ideal efficiency calculation is repeated. However, this calculation differs from the initial ideal efficiency calculation in that the number of particles in each size band is adjusted at each increment of the precipitator to include the additional particles which were reentrained into the gas flow due to rapping at that point. Thus the effluent particle statistics from this calculation will include the effects of the rapped dust being injected into the gas flow and recollected in subsequent sections of the precipitator. In order to describe a rapping schedule of any complexity, the ideal efficiency calculation must be performed many times. For this reason, it is recommended that the calculation be performed using all of the estimation procedures in order to reduce the computer time required. Subroutine LNDIST is required for the operation of this subroutine. Subroutines OPAC, MASARA, ARAOPT, and MIE are required if the opacity calculation is to be made.

When subroutine RAPPE is called by the main routine, the operations listed below are performed.

1. The ideal collection efficiency is corrected for unmodeled and nonideal effects. These corrections are the same as those described in the discussion of subroutine ADJUST.

2. Effluent particle statistics are calculated and printed. The amount of information which is printed depends on the value of the parameter NRAP (see Section 6 Volume II - Description of Output Data). The calculated data includes instantaneous particle size dependent statistics, instantaneous overall statistics (sum of all particle sizes), time-averaged statistics, and, if desired, plume opacity.

3. The thickness of the collected dust layer in each increment of the ESP is calculated.

4. If the final rap in the rapping scheme has occurred, outlet statistics averaged over the entire rapping cycle are calculated and printed. Following this, control is returned to the main routine which will expect to either terminate the calculation or read a different set of ESP data.

5. The dust layer thickness from the rapped increments are saved under a different variable name and are set to 0 in the dust layer thickness accumulator so that subsequent layer thickness calculations for these increments will begin on clean plates.

6. The fraction of the rapped dust that gets reentrained is described in terms of the number of particles in each size band so that the reentrained dust may be mixed with the particles already present in the gas flow at that point in the ESP. This is done through the use of the rapping profile and subroutine LNDIST. The rapping profile is an array of numbers which describes the dust being reentrained in terms of normalized quantity and log-normal size distribution as a function of time. The time dependence allows the cloud of dust resulting from the rap to be shaped in duration as well as in particle size. Subroutine LNDIST determines the fraction of particles in each size band for the log-normal distributions specified in the rapping profile. This information is then combined with the dust layer thicknesses from the rapped increments and the dimensions of the ESP to yield the number of particles in each size band per cubic meter of gas for each rapped increment. These numbers are stored in an array for use in subsequent collection efficiency calculations.

At this point, the model returns to the main routine for recalculation of the collection efficiency. During this calculation, the reentrained particles are included in the gas flow through the mechanism of adding the stored reentrained particles from increment i to the particles already present in the gas flow at the beginning of increment i + 1. In effect this assumes that all of the reentrained dust from increment i is uniformly distributed at the interface between increments i and i + 1 and that it has the same electrical charge as the other particles in the flow at that point. After the ideal efficiency of the inlet particles + reentrained dust is calculated, subroutine RAPPE is again called and the above steps are repeated with the exception of step 5 which occurs only once per rap. The process of calculating an ideal efficiency and calling subroutine RAPPE takes place n + 1 times for each schedules rap, where n is the number of time increments in the rapping profile.

The information exchange between subroutine RAPPE and the main program takes place in block common statements. Definitions of those variables which must be exchanged are listed below.

AS(I) - Collection plate area in each section (m^2)

ASNUCK - Fraction of gas sneakage and/or particle reentrainment without rapping

ATOTAL - Total collection plate area of the precipitator (m^2)

AZIGGY - Normalized standard deviation of the gas velocity distribution

AZNUMS - Number of stages over which gas sneakages and/or particle reentrainment without rapping occur

BS(I) - Wire-to-wire spacing in each section (in. or m)

DD - Mass density of the input particles (kg/m^3)

DIAM - Particle size diameter (m)

ENDPT - End points of the particle size bands

LINCS(I) - Incremental length in each section (ft or m)

LOOPR - Indicator which marks the end of the rapping cycle and returns the precipitator model to its normal processing sequence

LREEN - Indicator which causes the initialization of several accumulators

LSECT - Number of increments in each precipitator section

NRAP - Indicator used to specify whether dynamic rapping will be used and if so, what data will be printed

NREEN - Indicator which marks the first loop through the rapping cycle so that rapping data may be read

NUMSEC - Number of electrical sections in the precipitator

NWS(I) - Number of wires in each section

ONO - Initial number of particles in each size band per cubic meter of gas ($\#/m^3$)

PATHL - Path length for calculation of opacity (m)

PCNT - Fraction by mass of the different size bands at the inlet

RAD(J) - Radii of the different particle sizes (m)

RAPDST - Array containing number of particles in each size band per cubic meter of gas which are reintroduced into the gas flow in each increment of the precipitator by rapping (#/m^3)

THICK(I) - Dust layer deposition rate (mm/min)

TINC - Time required for gas to travel one increment (sec)

VG - Gas volume flow rate (m^3/sec)

WLS(I) - Total wire length in each section (ft or m)

XMV - Effective migration velocity in each size band under ideal conditions (m/sec)

XNO - Number of particles in each size band penetrating the precipitator per cubic meter of gas (#/m^3)

Of these variables, RAPDST is calculated in subroutine RAPPE. LOOPR, LREEN, and NREEN originate in the main program, are altered in RAPPE, and are used in both. The remaining variables are furnished to RAPPE from the main routine. A flow chart of subroutine RAPPE is shown in Figure 32.

Subroutine INTERN

This subroutine generates and prints a complete set of ESP V-I curves and operating points for a precipitator based on a study of 17 cold-side utility fly ash precipitators.[44] The input data required by this routine consists of only two items: ash resistivity and collection plate spacing. If only V-I data is required, program control returns to the main program following V-I curve printing.

If collection efficiency data is requested, the operating points generated from the V-I data are combined with a set of data from a typical utility ESP to form a complete data set. The length of the ESP is then varied so that efficiency calculations may be performed for SCA values of 40, 79, 119, and 158 m^2/m^3/sec (200, 400, 600, 800 ft^2/1000 acfm).

Figure 33 shows a flow chart for this subroutine. This subroutine is called by the main program. With the exception of the

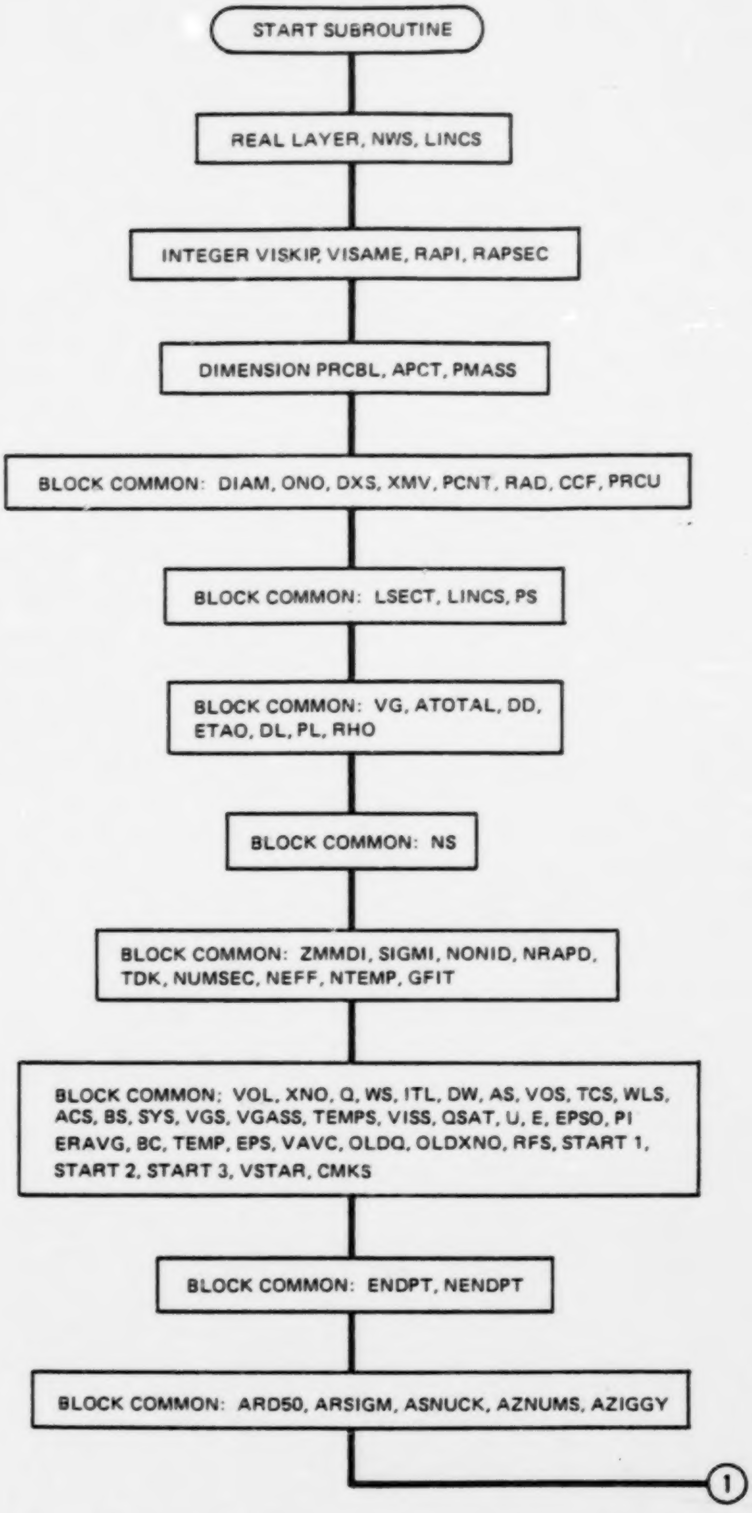

START SUBROUTINE
REAL LAYER, NWS, LINCS
INTEGER VISKIP, VISAME, RAPI, RAPSEC
DIMENSION PRCBL, APCT, PMASS
BLOCK COMMON: DIAM, ONO, DXS, XMV, PCNT, RAD, CCF, PRCU
BLOCK COMMON: LSECT, LINCS, PS
BLOCK COMMON: VG, ATOTAL, DD, ETAO, DL, PL, RHO
BLOCK COMMON: NS
BLOCK COMMON: ZMMDI, SIGMI, NONID, NRAPD, TDK, NUMSEC, NEFF, NTEMP, GFIT
BLOCK COMMON: VOL, XNO, Q, WS, ITL, DW, AS, VOS, TCS, WLS, ACS, BS, SYS, VGS, VGASS, TEMPS, VISS, QSAT, U, E, EPSO, PI ERAVG, BC, TEMP, EPS, VAVC, OLDQ, OLDXNO, RFS, START 1, START 2, START 3, VSTAR, CMKS
BLOCK COMMON: ENDPT, NENDPT
BLOCK COMMON: ARD50, ARSIGM, ASNUCK, AZNUMS, AZIGGY
1

Figure 32. Flow chart for subroutine RAPPE (Sheet 1 of 17).

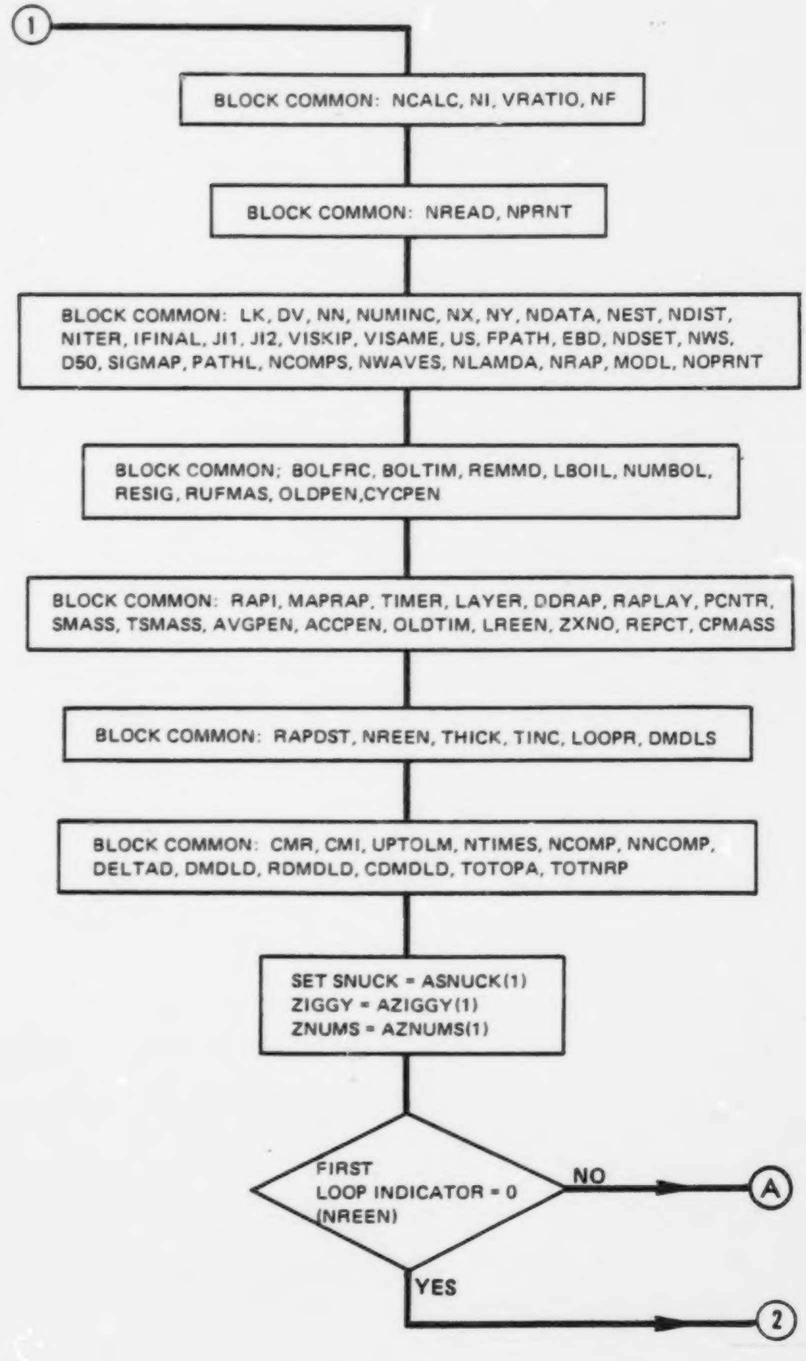

1
BLOCK COMMON: NCALC, NI, VRATIO, NF
BLOCK COMMON: NREAD, NPRNT
BLOCK COMMON: LK, DV, NN, NUMINC, NX, NY, NDATA, NEST, NDIST, NITER, IFINAL, JI1, JI2, VISKIP, VISAME, US, FPATH, EBD, NDSET, NWS, D50, SIGMAP, PATHL, NCOMPS, NWAVES, NLAMDA, NRAP, MODL, NOPRNT
BLOCK COMMON; BOLFRC, BOLTIM, REMMD, LBOIL, NUMBOL, RESIG, RUFMAS, OLDPEN,CYCPEN
BLOCK COMMON: RAPI, MAPRAP, TIMER, LAYER, DDRAP, RAPLAY, PCNTR, SMASS, TSMASS, AVGPEN, ACCPEN, OLDTIM, LREEN, ZXNO, REPCT, CPMASS
BLOCK COMMON: RAPDST, NREEN, THICK, TINC, LOOPR, DMDLS
BLOCK COMMON: CMR, CMI, UPTOLM, NTIMES, NCOMP, NNCOMP, DELTAD, DMDLD, RDMDLD, CDMDLD, TOTOPA, TOTNRP
SET SNUCK = ASNUCK(1)
ZIGGY = AZIGGY(1)
ZNUMS = AZNUMS(1)
FIRST
LOOP INDICATOR = 0
(NREEN)
NO
A
YES
2

Figure 32. Flow chart for subroutine RAPPE (Sheet 2 of 17).

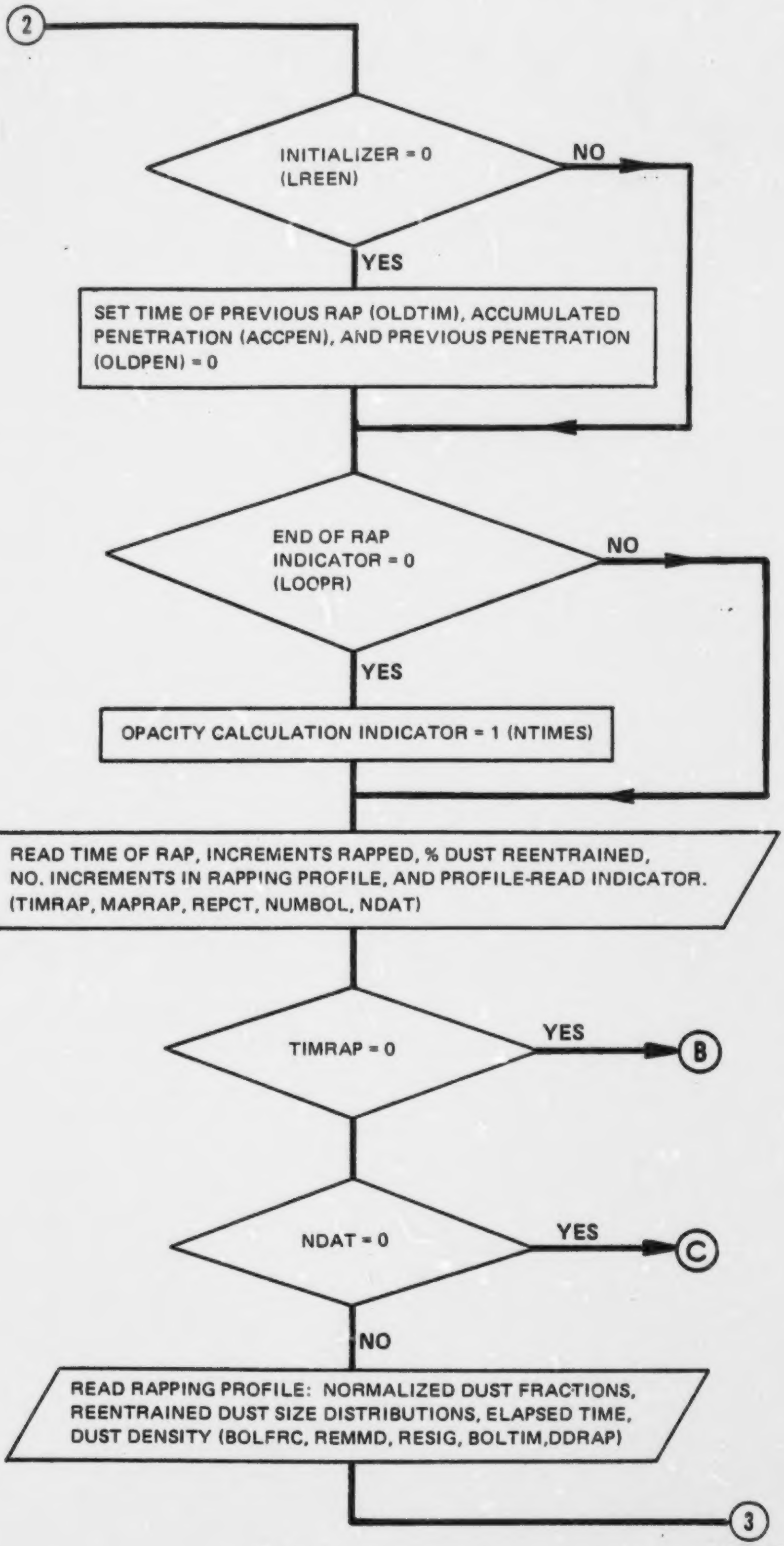

2
INITIALIZER = 0
(LREEN)
NO
YES
SET TIME OF PREVIOUS RAP (OLDTIM), ACCUMULATED PENETRATION (ACCPEN), AND PREVIOUS PENETRATION (OLDPEN) = 0
END OF RAP INDICATOR = 0 (LOOPR)
NO
YES
OPACITY CALCULATION INDICATOR = 1 (NTIMES)
READ TIME OF RAP, INCREMENTS RAPPED, % DUST REENTRAINED, NO. INCREMENTS IN RAPPING PROFILE, AND PROFILE-READ INDICATOR. (TIMRAP, MAPRAP, REPCT, NUMBOL, NDAT)
TIMRAP = 0
YES
B
NDAT = 0
YES
C
NO
READ RAPPING PROFILE: NORMALIZED DUST FRACTIONS, REENTRAINED DUST SIZE DISTRIBUTIONS, ELAPSED TIME, DUST DENSITY (BOLFRC, REMMD, RESIG, BOLTIM,DDRAP)
3

Figure 32. Flow chart for subroutine RAPPE (Sheet 3 of 17).

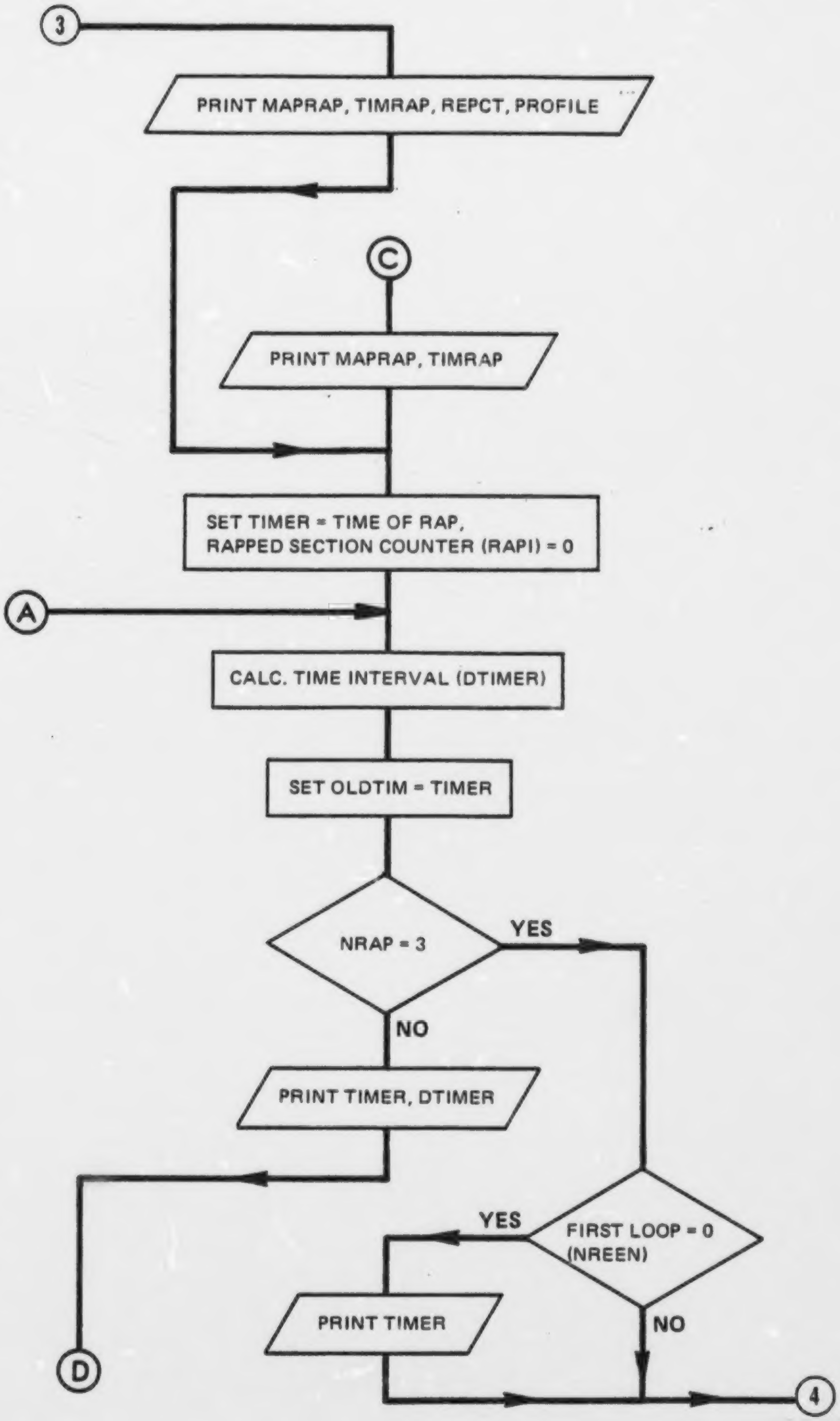

3
PRINT MAPRAP, TIMRAP, REPCT, PROFILE
C
PRINT MAPRAP, TIMRAP
SET TIMER = TIME OF RAP,
RAPPED SECTION COUNTER (RAPI) = 0
A
CALC. TIME INTERVAL (DTIMER)
SET OLDTIM = TIMER
NRAP = 3
YES
NO
PRINT TIMER, DTIMER
FIRST LOOP = 0
(NREEN)
YES
NO
PRINT TIMER
D
4

Figure 32. Flow chart for subroutine RAPPE (Sheet 4 of 17).

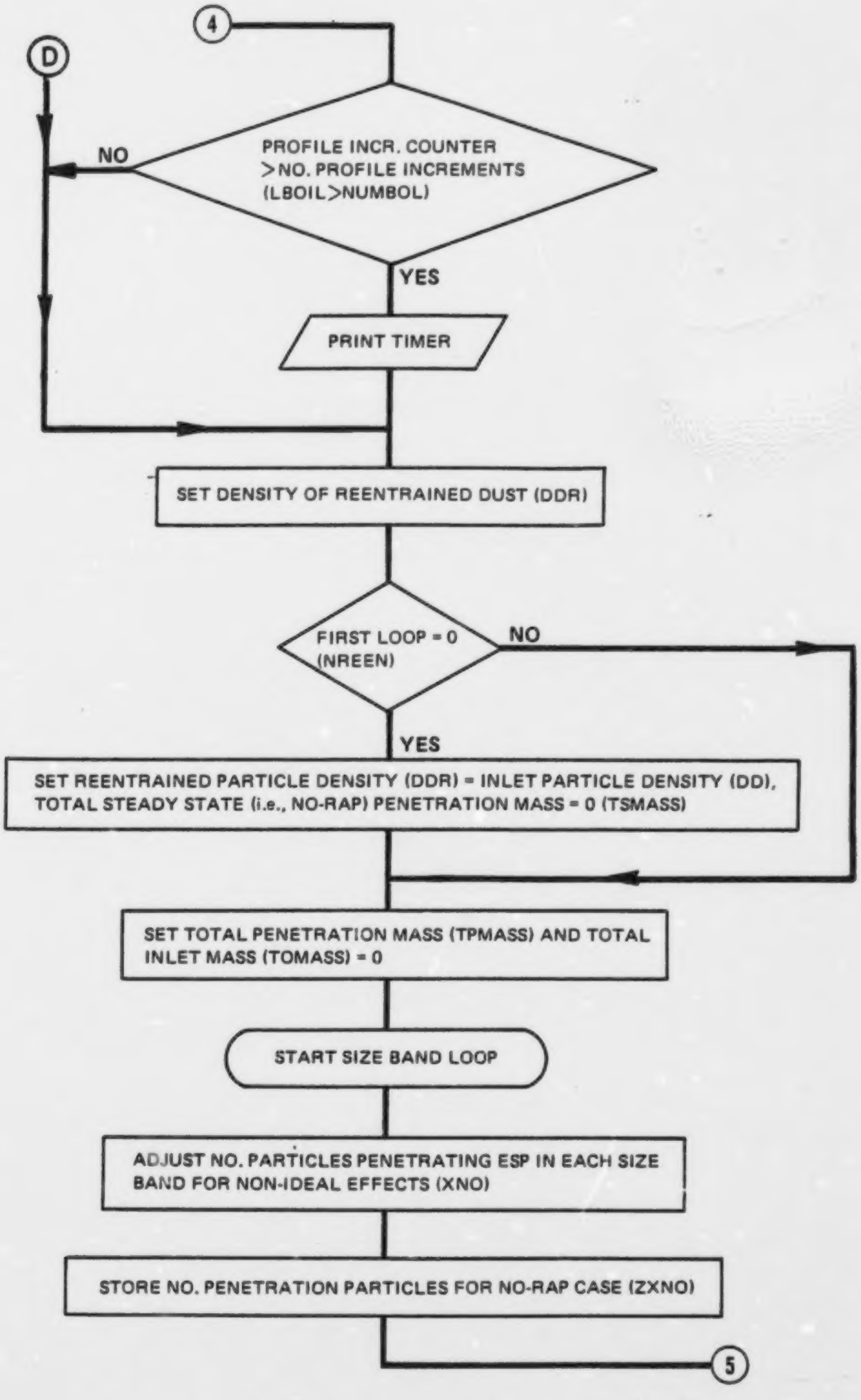

4
D
NO
PROFILE INCR. COUNTER >NO. PROFILE INCREMENTS (LBOIL>NUMBOL)
YES
PRINT TIMER
SET DENSITY OF REENTRAINED DUST (DDR)
FIRST LOOP = 0 (NREEN)
NO
YES
SET REENTRAINED PARTICLE DENSITY (DDR) = INLET PARTICLE DENSITY (DD), TOTAL STEADY STATE (i.e., NO-RAP) PENETRATION MASS = 0 (TSMASS)
SET TOTAL PENETRATION MASS (TPMASS) AND TOTAL INLET MASS (TOMASS) = 0
START SIZE BAND LOOP
ADJUST NO. PARTICLES PENETRATING ESP IN EACH SIZE BAND FOR NON-IDEAL EFFECTS (XNO)
STORE NO. PENETRATION PARTICLES FOR NO-RAP CASE (ZXNO)
5

Figure 32. Flow chart for subroutine RAPPE (Sheet 5 of 17).

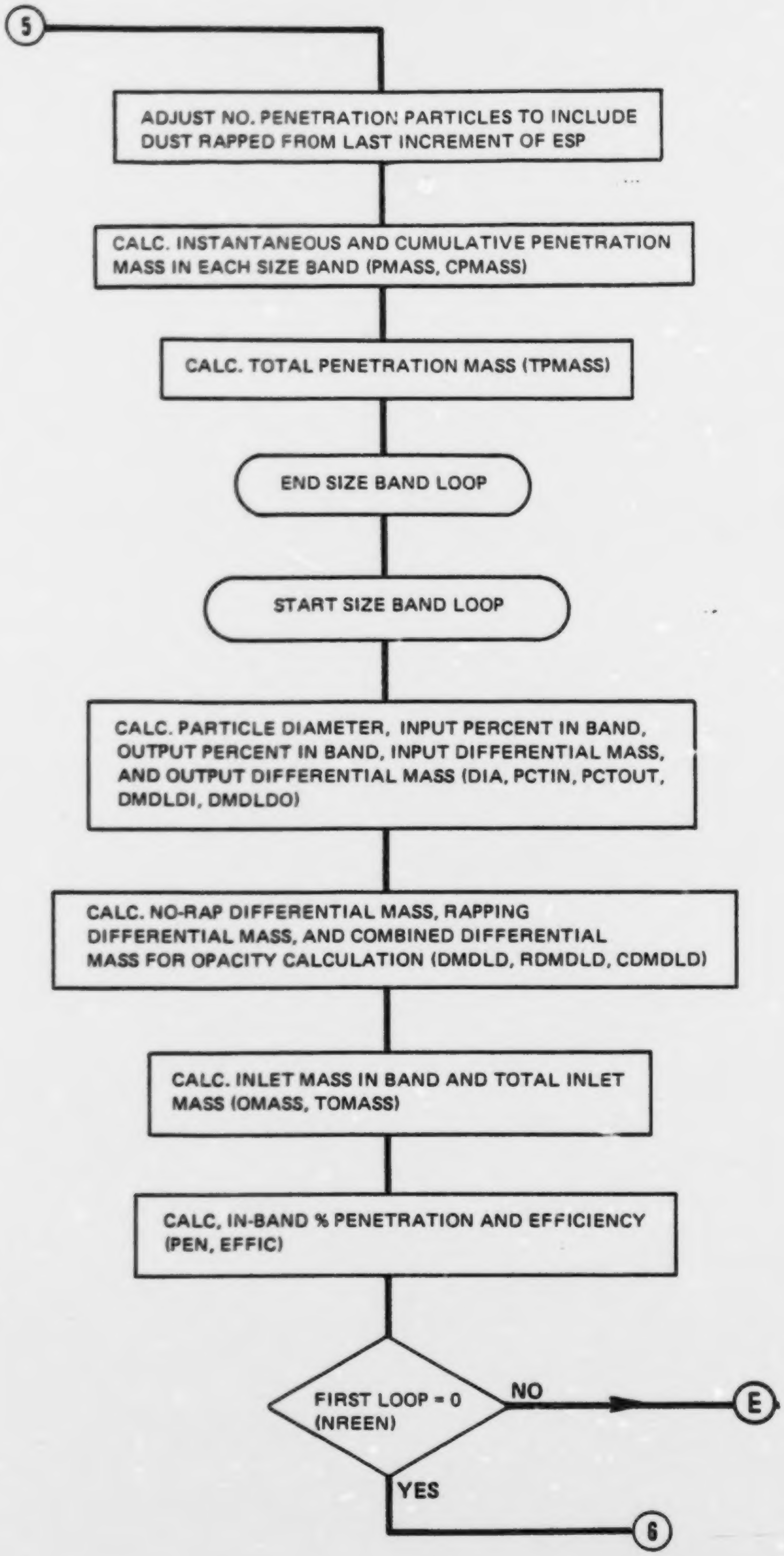

5
ADJUST NO. PENETRATION PARTICLES TO INCLUDE DUST RAPPED FROM LAST INCREMENT OF ESP
CALC. INSTANTANEOUS AND CUMULATIVE PENETRATION MASS IN EACH SIZE BAND (PMASS, CPMASS)
CALC. TOTAL PENETRATION MASS (TPMASS)
END SIZE BAND LOOP
START SIZE BAND LOOP
CALC. PARTICLE DIAMETER, INPUT PERCENT IN BAND, OUTPUT PERCENT IN BAND, INPUT DIFFERENTIAL MASS, AND OUTPUT DIFFERENTIAL MASS (DIA, PCTIN, PCTOUT, DMDLDI, DMDLDO)
CALC. NO-RAP DIFFERENTIAL MASS, RAPPING DIFFERENTIAL MASS, AND COMBINED DIFFERENTIAL MASS FOR OPACITY CALCULATION (DMDLD, RDMDLD, CDMDLD)
CALC. INLET MASS IN BAND AND TOTAL INLET MASS (OMASS, TOMASS)
CALC, IN-BAND % PENETRATION AND EFFICIENCY (PEN, EFFIC)
FIRST LOOP = 0 (NREEN)
NO
E
YES
6

Figure 32. Flow chart for subroutine RAPPE (Sheet 6 of 17).

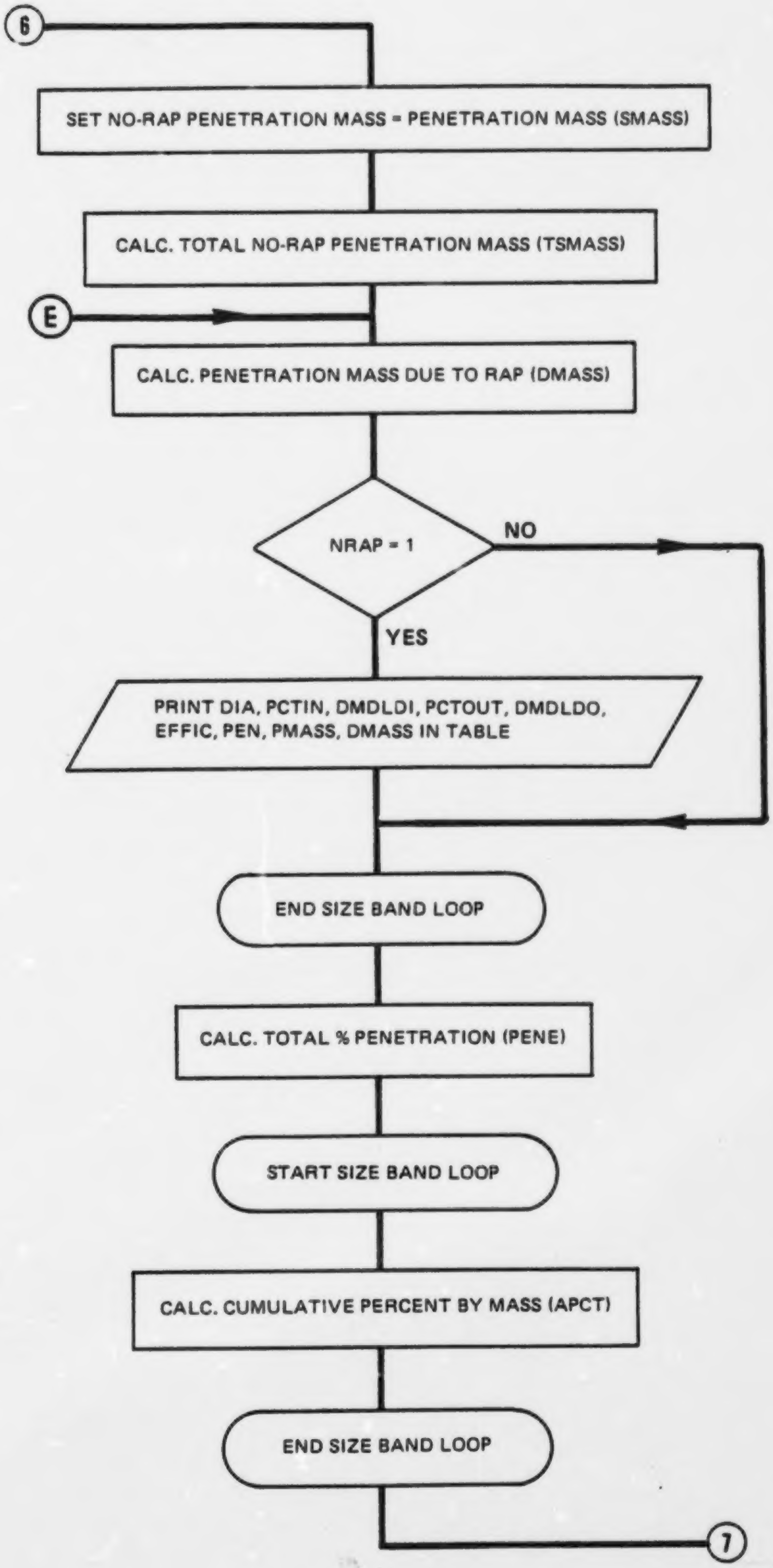

6
SET NO-RAP PENETRATION MASS = PENETRATION MASS (SMASS)
CALC. TOTAL NO-RAP PENETRATION MASS (TSMASS)
E
CALC. PENETRATION MASS DUE TO RAP (DMASS)
NRAP = 1
NO
YES
PRINT DIA, PCTIN, DMDLDI, PCTOUT, DMDLDO, EFFIC, PEN, PMASS, DMASS IN TABLE
END SIZE BAND LOOP
CALC. TOTAL % PENETRATION (PENE)
START SIZE BAND LOOP
CALC. CUMULATIVE PERCENT BY MASS (APCT)
END SIZE BAND LOOP
7

Figure 32. Flow chart for subroutine RAPPE (Sheet 7 of 17).

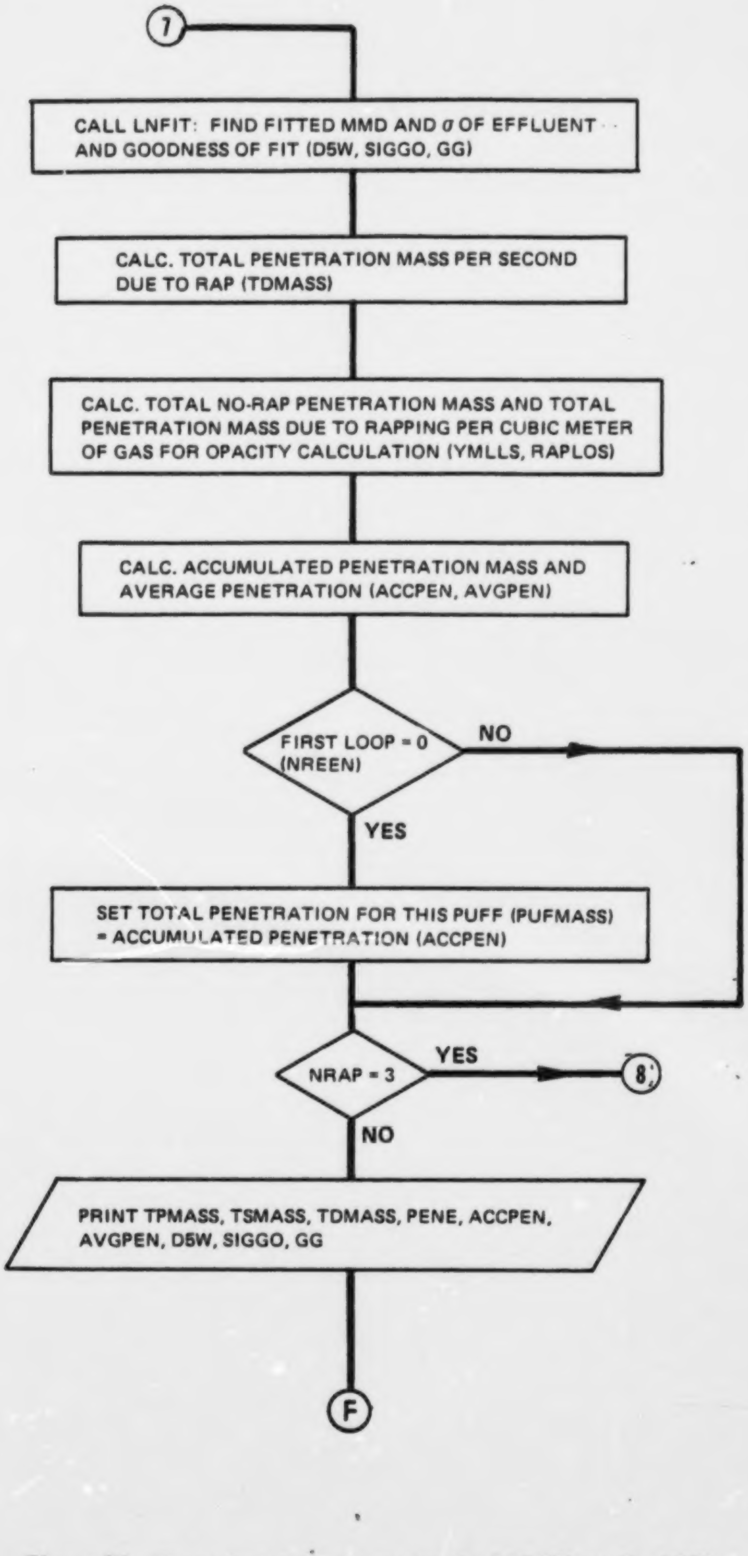

7
CALL LNFIT: FIND FITTED MMD AND σ OF EFFLUENT AND GOODNESS OF FIT (D5W, SIGGO, GG)
CALC. TOTAL PENETRATION MASS PER SECOND DUE TO RAP (TDMASS)
CALC. TOTAL NO-RAP PENETRATION MASS AND TOTAL PENETRATION MASS DUE TO RAPPING PER CUBIC METER OF GAS FOR OPACITY CALCULATION (YMLLS, RAPLOS)
CALC. ACCUMULATED PENETRATION MASS AND AVERAGE PENETRATION (ACCPEN, AVGPEN)
FIRST LOOP = 0 (NREEN)
NO
YES
SET TOTAL PENETRATION FOR THIS PUFF (PUFMASS) = ACCUMULATED PENETRATION (ACCPEN)
NRAP = 3
YES
8
NO
PRINT TPMASS, TSMASS, TDMASS, PENE, ACCPEN, AVGPEN, D5W, SIGGO, GG
F

Figure 32. Flow chart for subroutine RAPPE (Sheet 8 of 17).

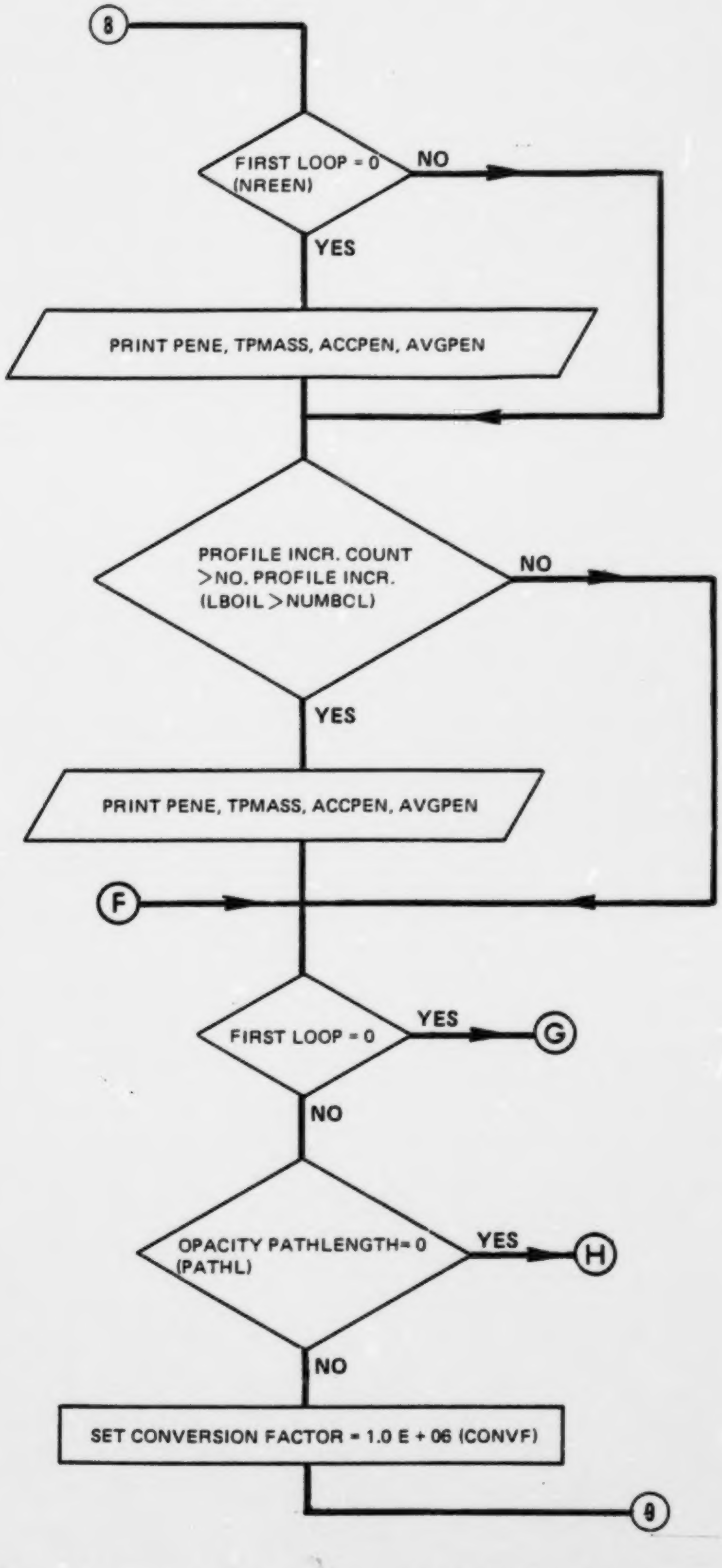

8
FIRST LOOP = 0
(NREEN)
NO
YES
PRINT PENE, TPMASS, ACCPEN, AVGPEN
PROFILE INCR. COUNT
>NO. PROFILE INCR.
(LBOIL>NUMBCL)
NO
YES
PRINT PENE, TPMASS, ACCPEN, AVGPEN
F
FIRST LOOP = 0
YES
G
NO
OPACITY PATHLENGTH= 0
(PATHL)
YES
H
NO
SET CONVERSION FACTOR = 1.0 E + 06 (CONVF)
9

Figure 32. Flow chart for subroutine RAPPE (Sheet 9 of 17).

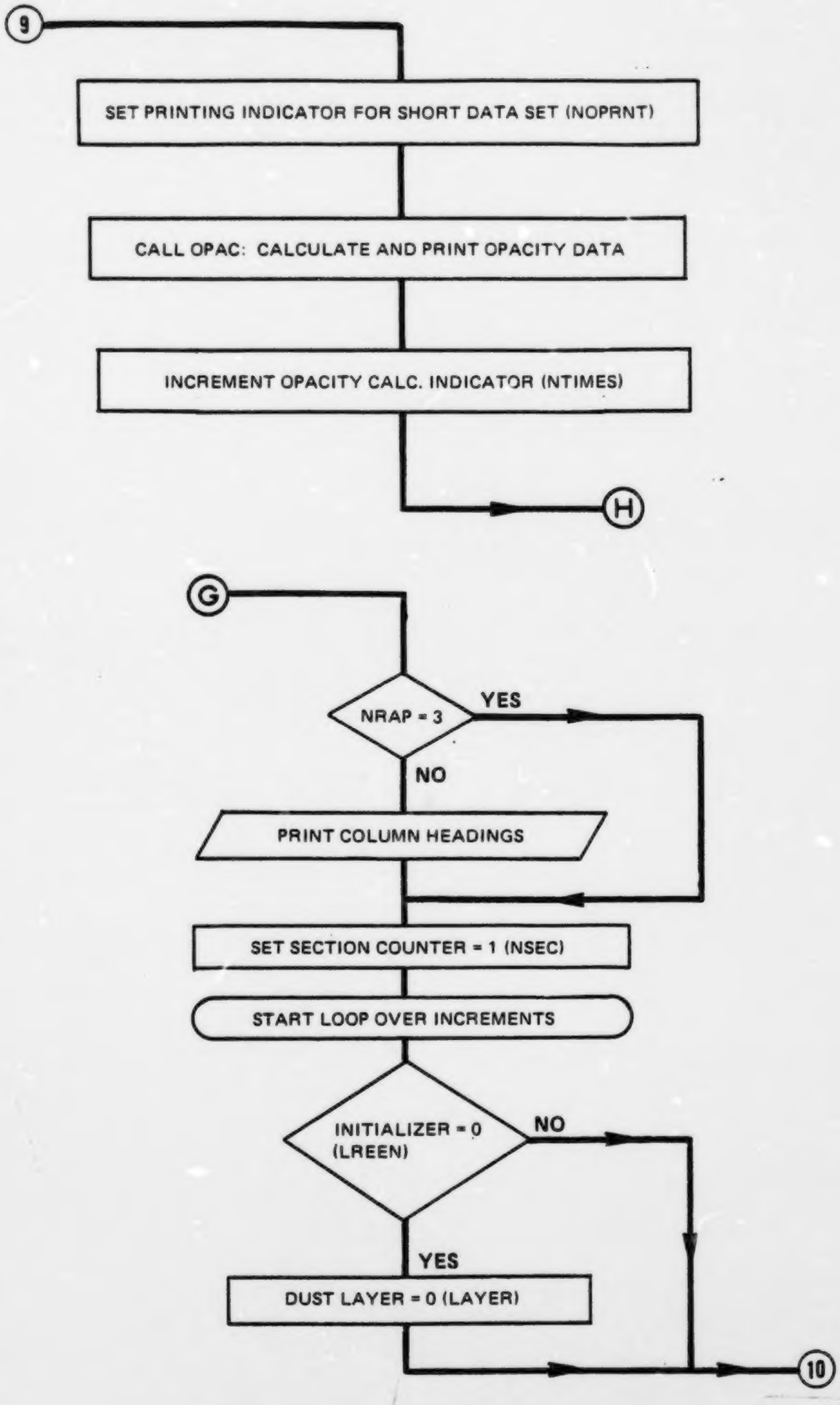

9
SET PRINTING INDICATOR FOR SHORT DATA SET (NOPRNT)
CALL OPAC: CALCULATE AND PRINT OPACITY DATA
INCREMENT OPACITY CALC. INDICATOR (NTIMES)
H
G
NRAP = 3
YES
NO
PRINT COLUMN HEADINGS
SET SECTION COUNTER = 1 (NSEC)
START LOOP OVER INCREMENTS
INITIALIZER = 0 (LREEN)
NO
YES
DUST LAYER = 0 (LAYER)
10

Figure 32. Flow chart for subroutine RAPPE (Sheet 10 of 17).

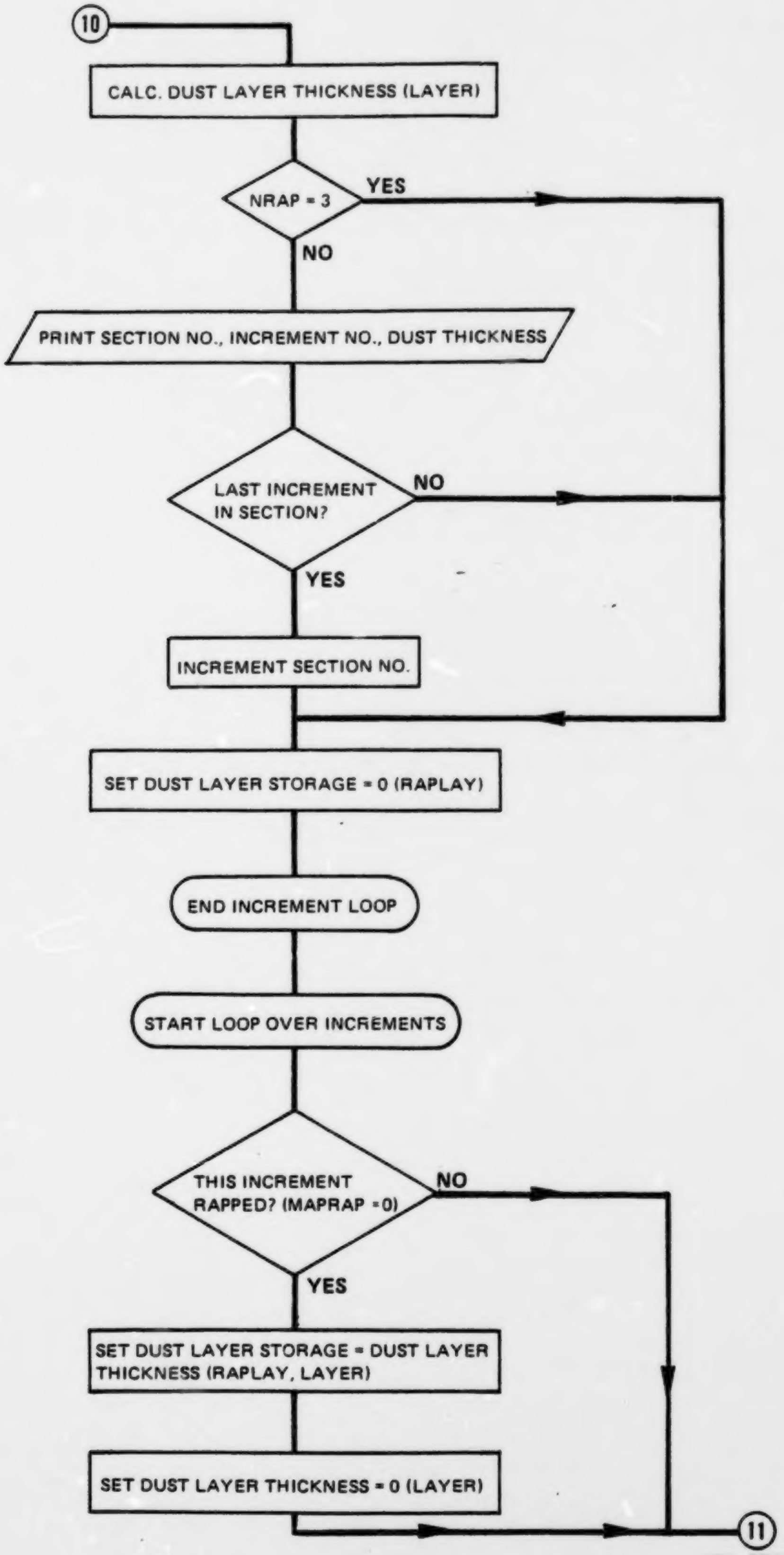
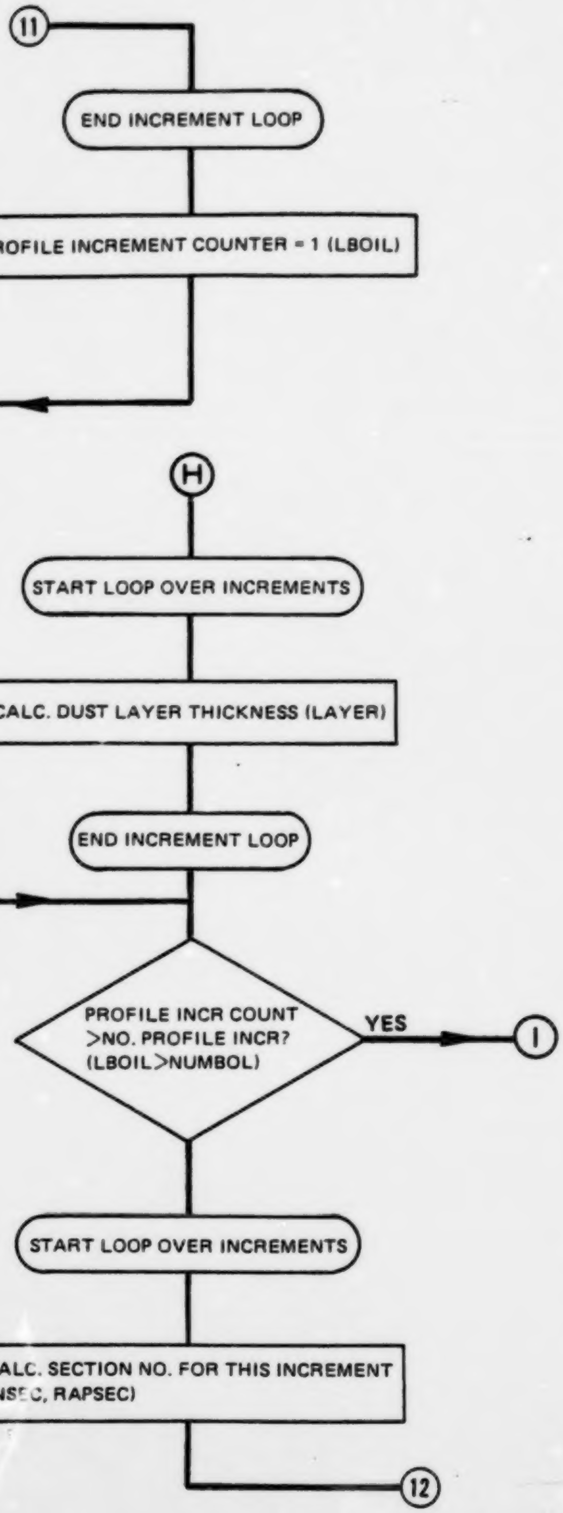
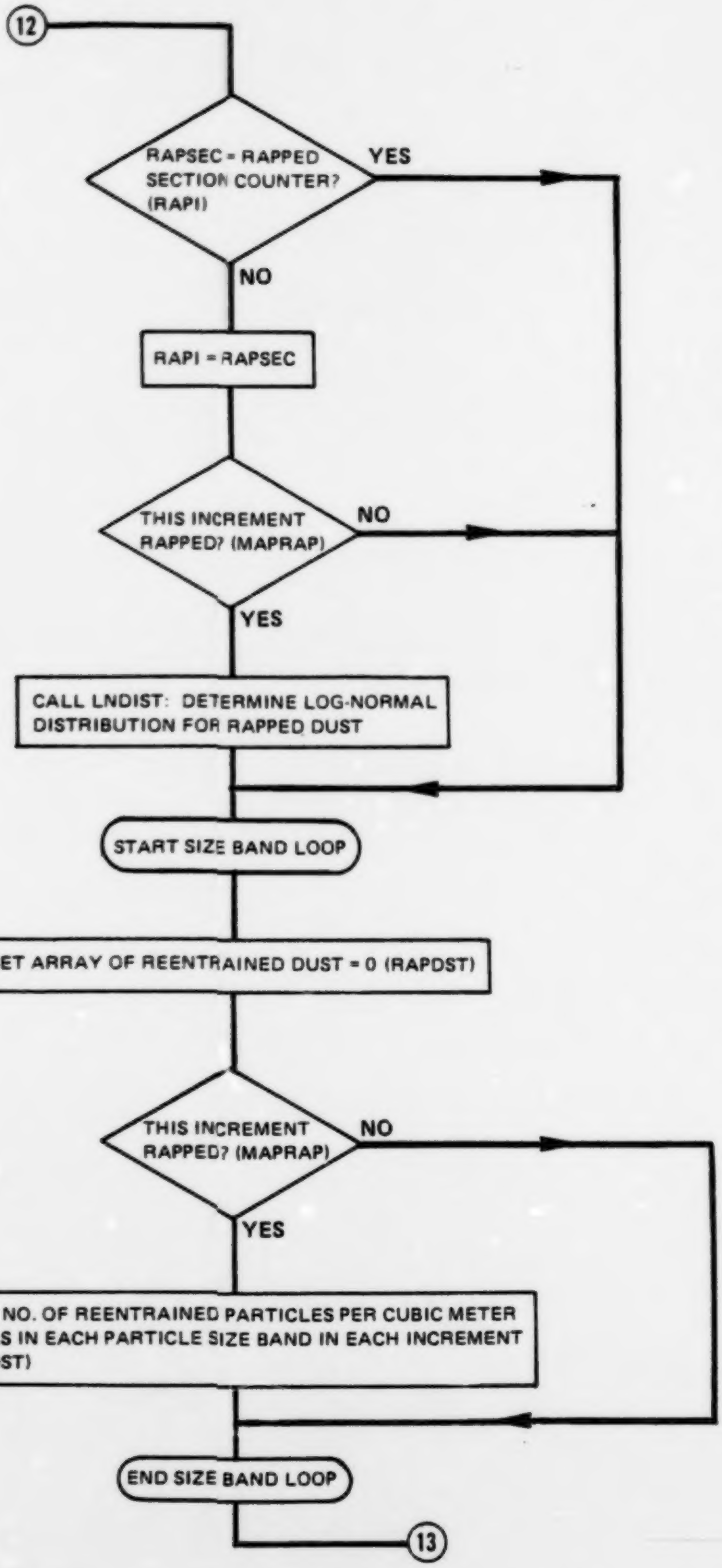

10
CALC. DUST LAYER THICKNESS (LAYER)
NRAP = 3
YES
NO
PRINT SECTION NO., INCREMENT NO., DUST THICKNESS
LAST INCREMENT IN SECTION?
NO
YES
INCREMENT SECTION NO.
SET DUST LAYER STORAGE = 0 (RAPLAY)
END INCREMENT LOOP
START LOOP OVER INCREMENTS
THIS INCREMENT RAPPED? (MAPRAP =0)
NO
YES
SET DUST LAYER STORAGE = DUST LAYER THICKNESS (RAPLAY, LAYER)
SET DUST LAYER THICKNESS = 0 (LAYER)
11

Figure 32. Flow chart for subroutine RAPPE (Sheet 11 of 17).



11
END INCREMENT LOOP
PROFILE INCREMENT COUNTER = 1 (LBOIL)
H
START LOOP OVER INCREMENTS
CALC. DUST LAYER THICKNESS (LAYER)
END INCREMENT LOOP
PROFILE INCR COUNT >NO. PROFILE INCR? (LBOIL>NUMBOL)
YES
I
START LOOP OVER INCREMENTS
CALC. SECTION NO. FOR THIS INCREMENT (NSEC, RAPSEC)
12

Figure 32. Flow chart for subroutine RAPPE (Sheet 12 of 17).



12
RAPSEC = RAPPED SECTION COUNTER? (RAPI)
YES
NO
RAPI = RAPSEC
THIS INCREMENT RAPPED? (MAPRAP)
NO
YES
CALL LNDIST: DETERMINE LOG-NORMAL DISTRIBUTION FOR RAPPED DUST
START SIZE BAND LOOP
SET ARRAY OF REENTRAINED DUST = 0 (RAPDST)
THIS INCREMENT RAPPED? (MAPRAP)
NO
YES
CALC. NO. OF REENTRAINED PARTICLES PER CUBIC METER OF GAS IN EACH PARTICLE SIZE BAND IN EACH INCREMENT (RAPDST)
END SIZE BAND LOOP
13

Figure 32. Flow chart for subroutine RAPPE (Sheet 13 of 17).

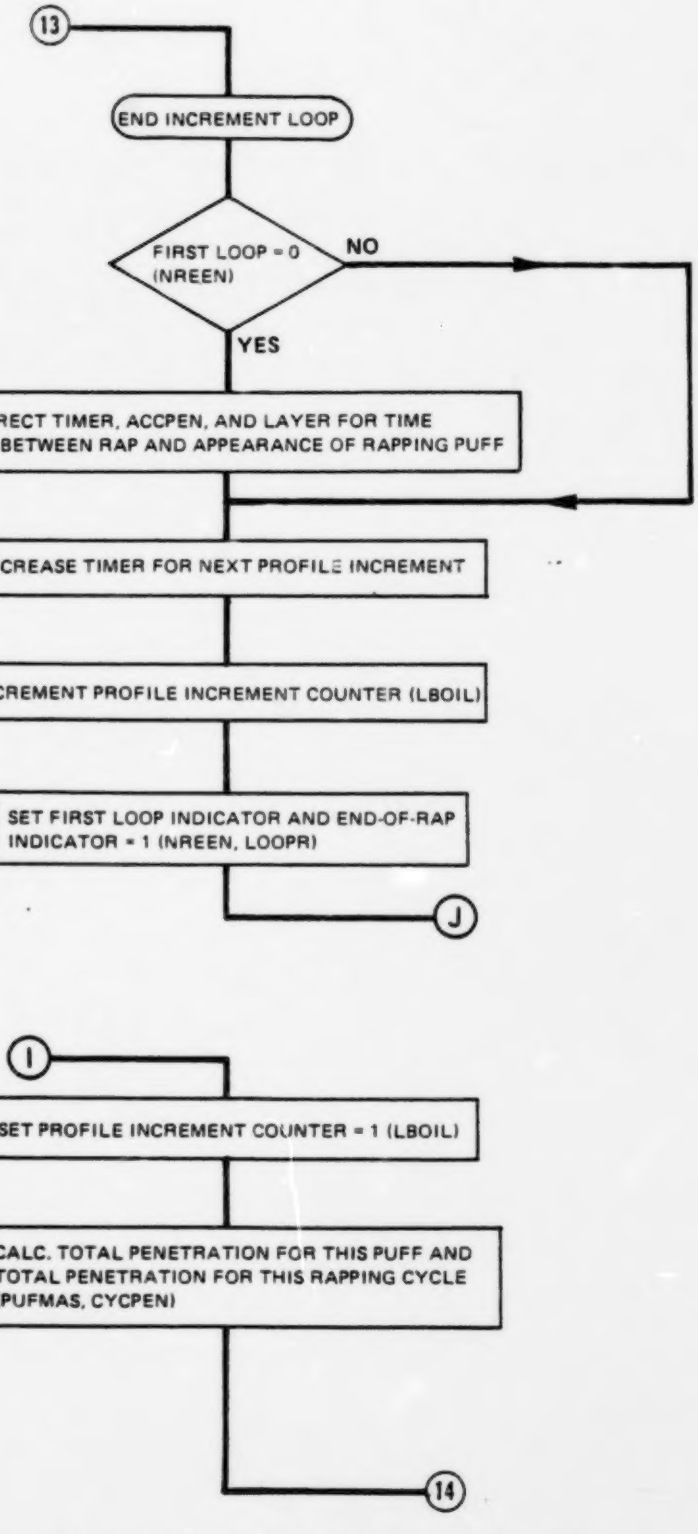
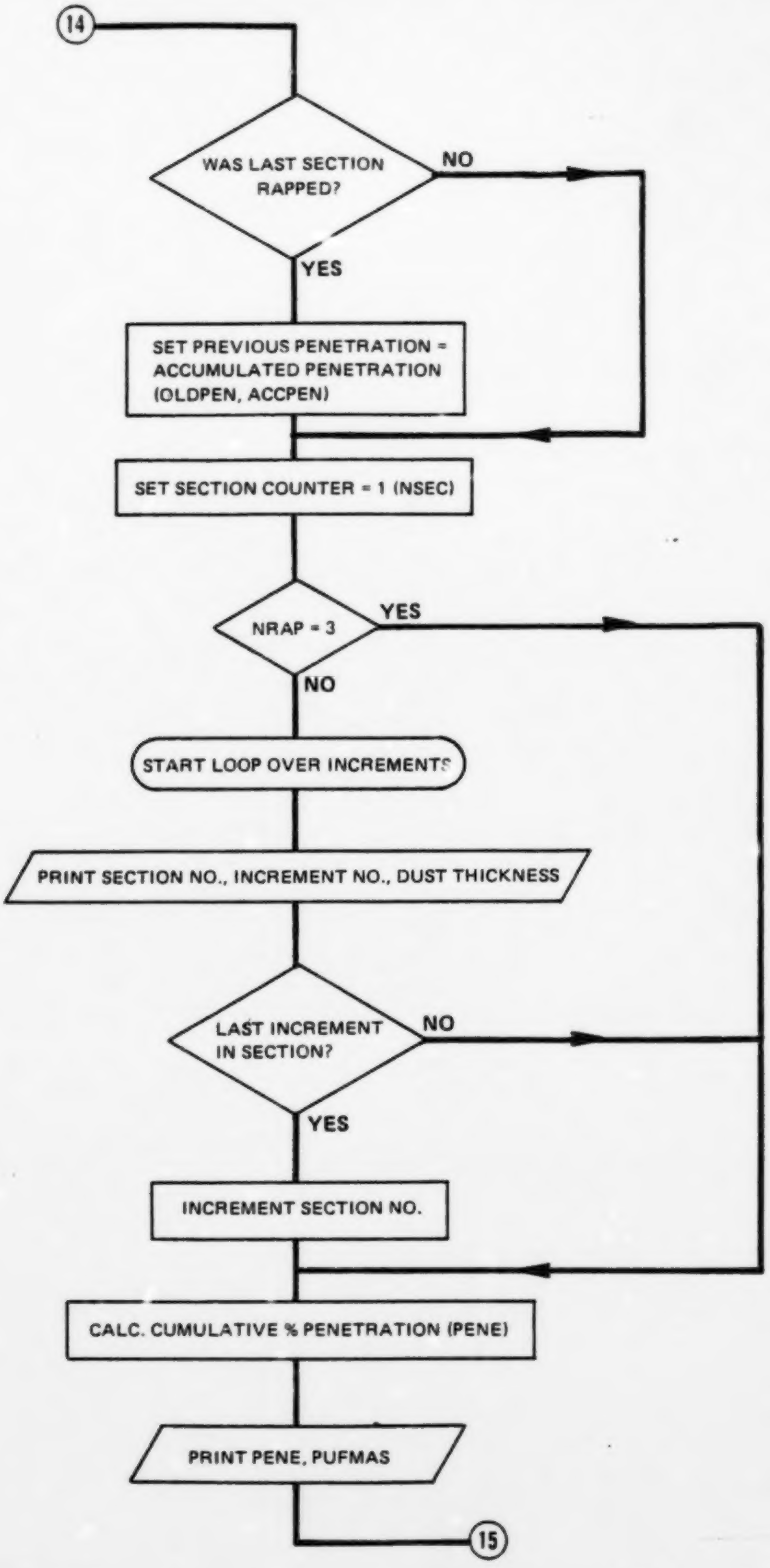

13
END INCREMENT LOOP
FIRST LOOP = 0 (NREEN)
NO
YES
CORRECT TIMER, ACCPEN, AND LAYER FOR TIME LAG BETWEEN RAP AND APPEARANCE OF RAPPING PUFF
INCREASE TIMER FOR NEXT PROFILE INCREMENT
INCREMENT PROFILE INCREMENT COUNTER (LBOIL)
SET FIRST LOOP INDICATOR AND END-OF-RAP INDICATOR = 1 (NREEN, LOOPR)
J
I
SET PROFILE INCREMENT COUNTER = 1 (LBOIL)
CALC. TOTAL PENETRATION FOR THIS PUFF AND TOTAL PENETRATION FOR THIS RAPPING CYCLE (PUFMAS, CYCPEN)
14

Figure 32. Flow chart for subroutine RAPPE (Sheet 14 of 17).



14
WAS LAST SECTION RAPPED?
NO
YES
SET PREVIOUS PENETRATION = ACCUMULATED PENETRATION (OLDPEN, ACCPEN)
SET SECTION COUNTER = 1 (NSEC)
NRAP = 3
YES
NO
START LOOP OVER INCREMENTS
PRINT SECTION NO., INCREMENT NO., DUST THICKNESS
LAST INCREMENT IN SECTION?
NO
YES
INCREMENT SECTION NO.
CALC. CUMULATIVE % PENETRATION (PENE)
PRINT PENE, PUFMAS
15

Figure 32. Flow chart for subroutine RAPPE (Sheet 15 of 17).

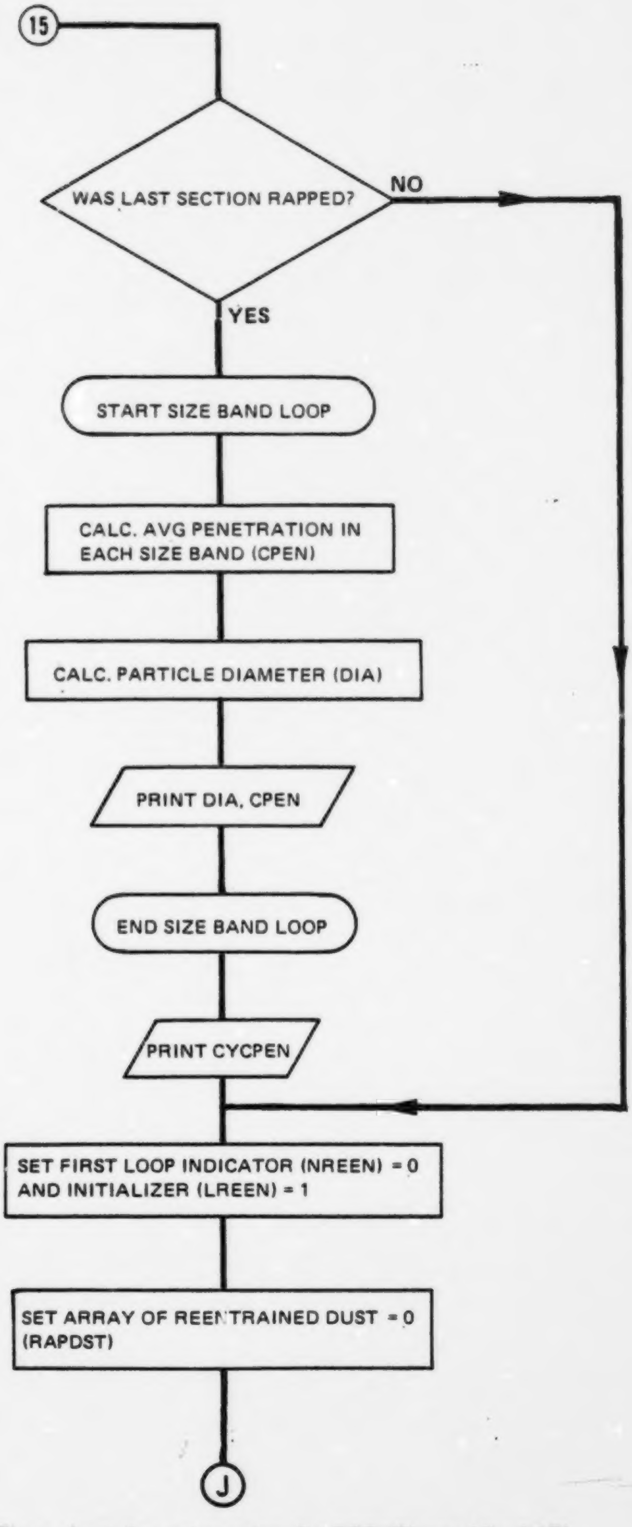

15
WAS LAST SECTION RAPPED?
NO
YES
START SIZE BAND LOOP
CALC. AVG PENETRATION IN EACH SIZE BAND (CPEN)
CALC. PARTICLE DIAMETER (DIA)
PRINT DIA, CPEN
END SIZE BAND LOOP
PRINT CYCPEN
SET FIRST LOOP INDICATOR (NREEN) = 0 AND INITIALIZER (LREEN) = 1
SET ARRAY OF REENTRAINED DUST = 0 (RAPDST)
J

Figure 32. Flow chart for subroutine RAPPE (Sheet 16 of 17).

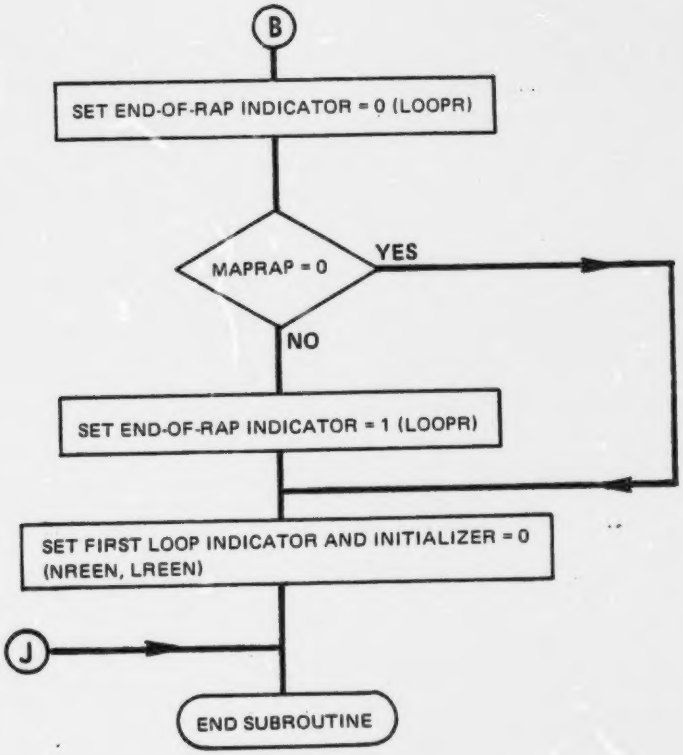

B
SET END-OF-RAP INDICATOR = 0 (LOOPR)
MAPRAP = 0
YES
NO
SET END-OF-RAP INDICATOR = 1 (LOOPR)
SET FIRST LOOP INDICATOR AND INITIALIZER = 0 (NREEN, LREEN)
J
END SUBROUTINE

Figure 32. Flow chart for subroutine RAPPE (Sheet 17 of 17).

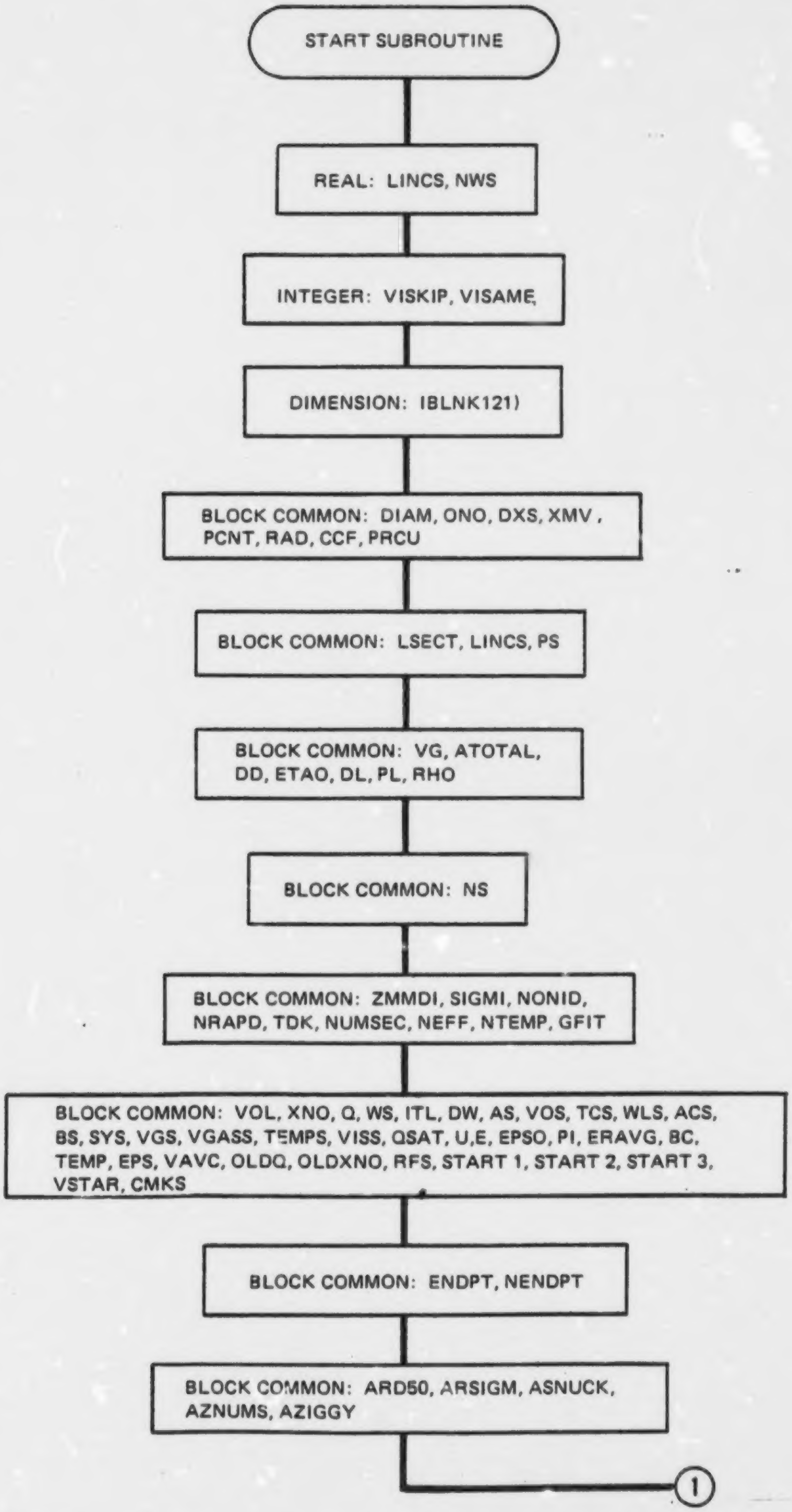

START SUBROUTINE
REAL: LINCS, NWS
INTEGER: VISKIP, VISAME
DIMENSION: IBLNK121)
BLOCK COMMON: DIAM, ONO, DXS, XMV, PCNT, RAD, CCF, PRCU
BLOCK COMMON: LSECT, LINCS, PS
BLOCK COMMON: VG, ATOTAL, DD, ETAO, DL, PL, RHO
BLOCK COMMON: NS
BLOCK COMMON: ZMMDI, SIGMI, NONID, NRAPD, TDK, NUMSEC, NEFF, NTEMP, GFIT
BLOCK COMMON: VOL, XNO, Q, WS, ITL, DW, AS, VOS, TCS, WLS, ACS, BS, SYS, VGS, VGASS, TEMPS, VISS, QSAT, U,E, EPSO, PI, ERAVG, BC, TEMP, EPS, VAVC, OLDQ, OLDXNO, RFS, START 1, START 2, START 3, VSTAR, CMKS
BLOCK COMMON: ENDPT, NENDPT
BLOCK COMMON: ARD50, ARSIGM, ASNUCK, AZNUMS, AZIGGY
①

Figure 33. Flow chart for subroutine INTERN (Sheet 1 of 3).

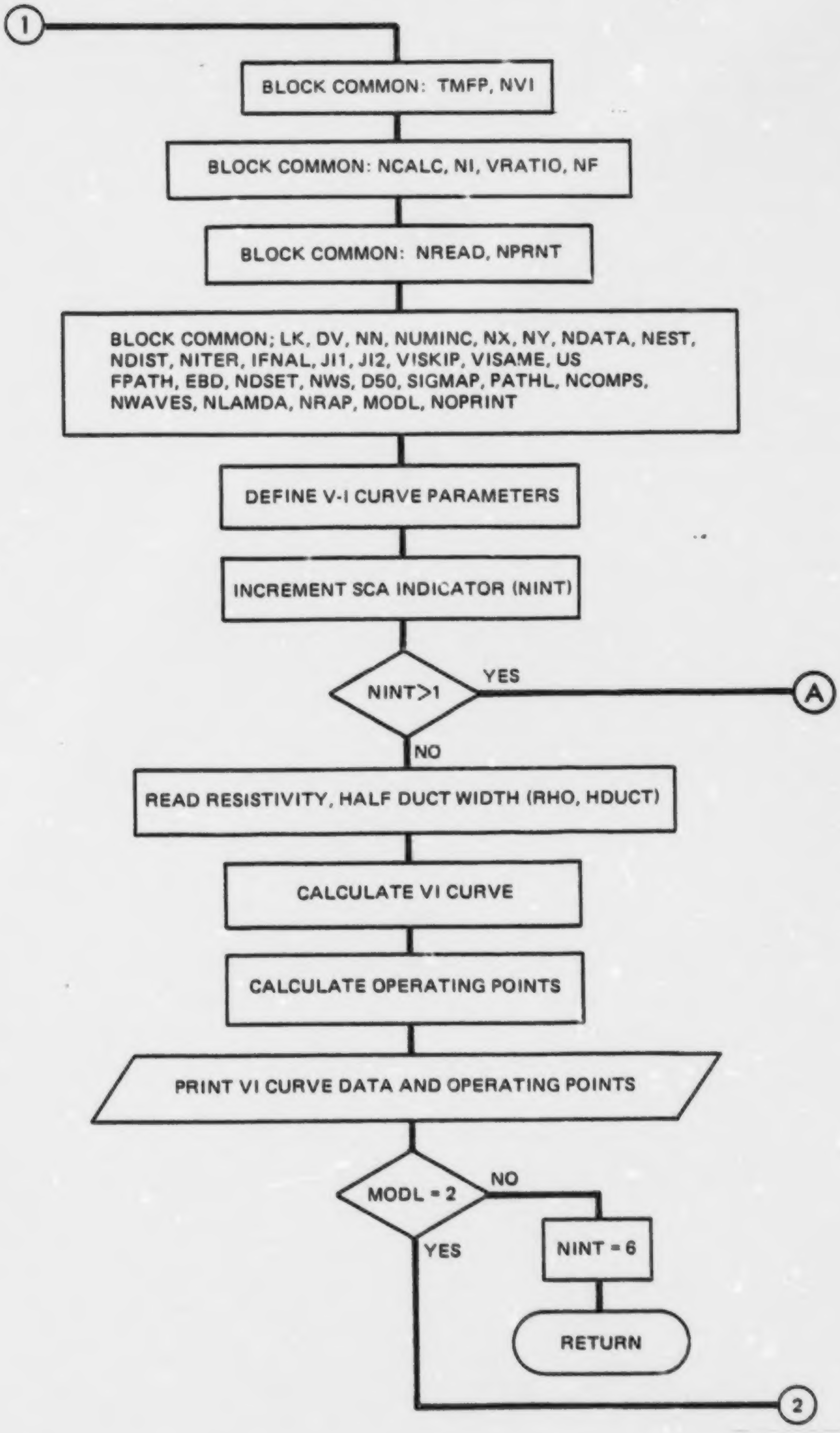

1
BLOCK COMMON: TMFP, NVI
BLOCK COMMON: NCALC, NI, VRATIO, NF
BLOCK COMMON: NREAD, NPRNT
BLOCK COMMON; LK, DV, NN, NUMINC, NX, NY, NDATA, NEST, NDIST, NITER, IFNAL, JI1, JI2, VISKIP, VISAME, US FPATH, EBD, NDSET, NWS, D50, SIGMAP, PATHL, NCOMPS, NWAVES, NLAMDA, NRAP, MODL, NOPRINT
DEFINE V-I CURVE PARAMETERS
INCREMENT SCA INDICATOR (NINT)
NINT>1
YES
A
NO
READ RESISTIVITY, HALF DUCT WIDTH (RHO, HDUCT)
CALCULATE VI CURVE
CALCULATE OPERATING POINTS
PRINT VI CURVE DATA AND OPERATING POINTS
MODL = 2
NO
NINT = 6
RETURN
YES
2

Figure 33. Flow chart for subroutine INTERN (Sheet 2 of 3).

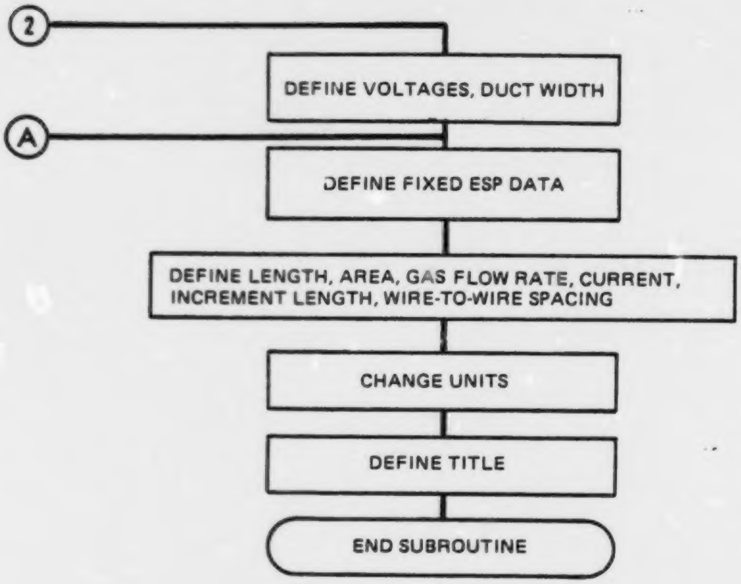

2
DEFINE VOLTAGES, DUCT WIDTH
A
DEFINE FIXED ESP DATA
DEFINE LENGTH, AREA, GAS FLOW RATE, CURRENT, INCREMENT LENGTH, WIRE-TO-WIRE SPACING
CHANGE UNITS
DEFINE TITLE
END SUBROUTINE

Figure 33. Flow chart for subroutine INTERN (Sheet 3 of 3).

SCA counter, NINT, the data exchange between this subroutine and the main program occurs through block common statements. Definitions of the variables passed between INTERN and MAIN are given below.

ACS(I) - Corona wire radii for the different linear electrical sections (in.)

AS(I) - Collection plate areas for the different linear electrical sections (m^2)

ASNUCK(JJ) - Fractions of gas sneakage and/or particle reentrainment without rapping

AZIGGY(JJ) - Normalized standard deviations of the gas velocity distribution

AZNUMS(JJ) - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur

BS(I) - Wire-to-plate spacing for the different linear electrical sections (in.)

D50 - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

DD - Mass density of the particles (kg/m^3)

DL - Inlet mass loading (grains/ft^3)

DV - Total volume per cubic meter of gas occupied by particles [m^3(particles)/m^3(gas)]

EBD - Electrical breakdown strength of the gas near the collection electrode or the collected particulate layer (V/m)

ENDPT(L) - Particle diameters in the inlet cumulative percent by mass distribution (μm)

EPS - Relative dielectric constant of the particles

ETAO - Estimated or design overall mass collection efficiency (%)

FPATH - Factor which scales the ion mean free path

ITL(M) - Identifying label for the calculations

LINCS(I) - Lengths of the increments taken in the different linear electrical sections (ft)

LSECT(I) - Number of length increments in the different linear electrical sections

NCALC - Indicator which determines whether to use equation (12) for particle charging or the sum of the classical field and diffusion charges

NDATA - Indicator which determines the type of data set that is to be read into the program

NDIST - Indicator which specifies whether the user is to supply the inlet particle size distribution or the program is to calculate a log-normal distribution

NEFF - Indicator which determines whether the unadjusted, ideal or adjusted, no-rap efficiency is used to determine the mass reentrained due to rapping

NENDPT - Number of particle diameters in the inlet cumulative percent by mass distribution

NEST - Indicator which specifies whether to use extensive calculations or estimation procedures in determining precipitator performance

NINT - Counter used to keep tract of SCA values

NITER - Indicator which determines the maximum number of iterations over a loop that converges on overall mass efficiency or the number of iterations that will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions

NN - Number of increments in the Runge-Kutta integration of equation (12)

NONID - Number of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered

NOPRNT - Indicator used to suppress printing of all charging data and some opacity data

NRAPD - Number of rapping puff particle size distributions to be considered

NS - Number of different particle size bands in the inlet particle size distribution

NTEMP - Indicator which specifies whether the precipitator is cold or hot side

NUMSEC - Number of linear electrical sections in the precipitator

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

NWS(I) - Number of wires per electrical section per gas passage for the different linear electrical sections

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

PATHL - Pathlength for opacity calculation (ft)

PL - Total electrical length of the precipitator (ft)

PS(I) - Gas pressure in the different electrical sections (atm)

RHO - Resistivity of the collected particulate layer (ohm-cm)

SIGMAP - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

SYS(I) - One-half the wire-to-wire spacing for the different linear electrical sections (in.)

TEMPS(I) - Gas temperature for the different linear electrical sections (°F)

TCS(I) - Total current for the different linear electrical sections (A)

US - Ion mobility at standard temperature and pressure (reduced ion mobility)

VGASS(I) - Gas velocity for the different linear electrical sections (ft/sec)

VGS(I) - Gas volume flow rate for the different linear electrical sections (ft^3/min)

VISS(I) - Gas viscosity for the different linear electrical sections (kg/m-sec)

VOS(I) - Applied voltages for the different linear electrical sections (V)

VRATIO - Ratio of the peak applied voltage to the average for use in particle charging

WLS(I) - Total wire length for the different linear electrical sections (ft)

Of the above variables, only the value of NINT is supplied by the main program. All of the remaining variables are supplied by the subroutine.

Subroutine CHEKIN

This subroutine checks each item in the basic data set and prints a warning message if either of the two conditions listed below occur.

1. A variable has a value which lies outside of the range allowed by the model. This warning indicates an error in the input data which will result in either abnormal termination of the model or incorrect output values. Examples of errors which cause this warning are more than 21 size band endpoints, more than 45 increments, and less endpoints read in than specified (i.e., missing data).

2. A variable has a value which is unusual for an industrial precipitator. If one of the values of the operating conditions or physical dimensions of the ESP falls outside a range of values given in this subroutine, a warning to check the variable in question will occur. This does not mean that the variable is erroneous, but merely that it has an unusual value. For example, laboratory scale precipitator data will trigger warnings regarding the plate area, applied current, and gas flow rate because these values are much smaller than values found in industrial units. This warning will also be printed if the data in question is missing.

This subroutine is called from subroutine PRTINP, which prints the input data, so that all warnings will appear on the printed output before any other data is printed. Note that the absence of a warning message does not mean that the input data is correct. The data may have incorrect values which fall within the acceptable range of values as defined by this subroutine. However, this subroutine will identify large data errors or missing data.

Subroutines PRTINP, PRTINC, PRTCHG, and PRTSUM

Subroutines PRTINP, PRTINC, PRTCHG, and PRTSUM perform the function of printing out information of importance to the user. Since these subroutines do not involve operations based on physical principles or numerical techniques, they will not be discussed in detail. However, the output from these subroutines is discussed in detail in Volume II. Briefly, PRTINP prints out all the input data to the program, PRTINC prints out the results of calculations which are a function of incremental length through the precipitator, PRTCHG prints out information concerning the charge on each particle size in each incremental length through the precipitator, and PRTSUM prints out a summary table of precipitator performance and operating parameters.

SECTION 8

DESCRIPTION OF INPUT DATA

GENERAL DESCRIPTION

The format of the original computer program which performs the calculations in the model for electrostatic precipitation has been re-structured to make the inputting of data less cumbersome. The number of cards which is necessary to input data has been reduced significantly by allowing different operating conditions to be analyzed from one basic set of input data. Due to the fact that several options are available in using the model, the number of cards and type of information in the input data may vary from one set of data to the next. Thus, it is necessary for the user to familiarize himself with the logic associated with the input data in order to ensure that the desired operations will be performed.

The input variables may be read into the program entirely in metric units or in mixed British and metric units depending on the value of the variable MODL described below. All input data are converted to metric units prior to performing the calculations. The input variables and format specifications are discussed in detail in the following subsection. Where both British and metric units are given, the British units are to be used when mixed units are selected and the metric when all-metric input is selected. Figure 34 contains a flow chart which shows the logic involved in entering the data.

CONSTRUCTION OF THE BASIC DATA SET

The following is a sequential listing of the variables in the first group of data which is read in, along with the descriptions of the variables and the format specifications.

(1) NENDPT is the number of discrete points on a cumulative percent versus particle diameter curve. NENDPT is specified by the user and must have a value of at least 1 but not greater than 21. After the collection efficiency has been calculated for one data set, the program will begin reading data for another efficiency calculation starting with this data group. If NENDPT has a value of 99, the program terminates. Thus this data group will be the first group of each data set and will also be the final card in the input data. If 21<NENDPT<99, the program will terminate abnormally during execution. NENDPT is read in with an I2 format and must be right justified in columns 1-2.

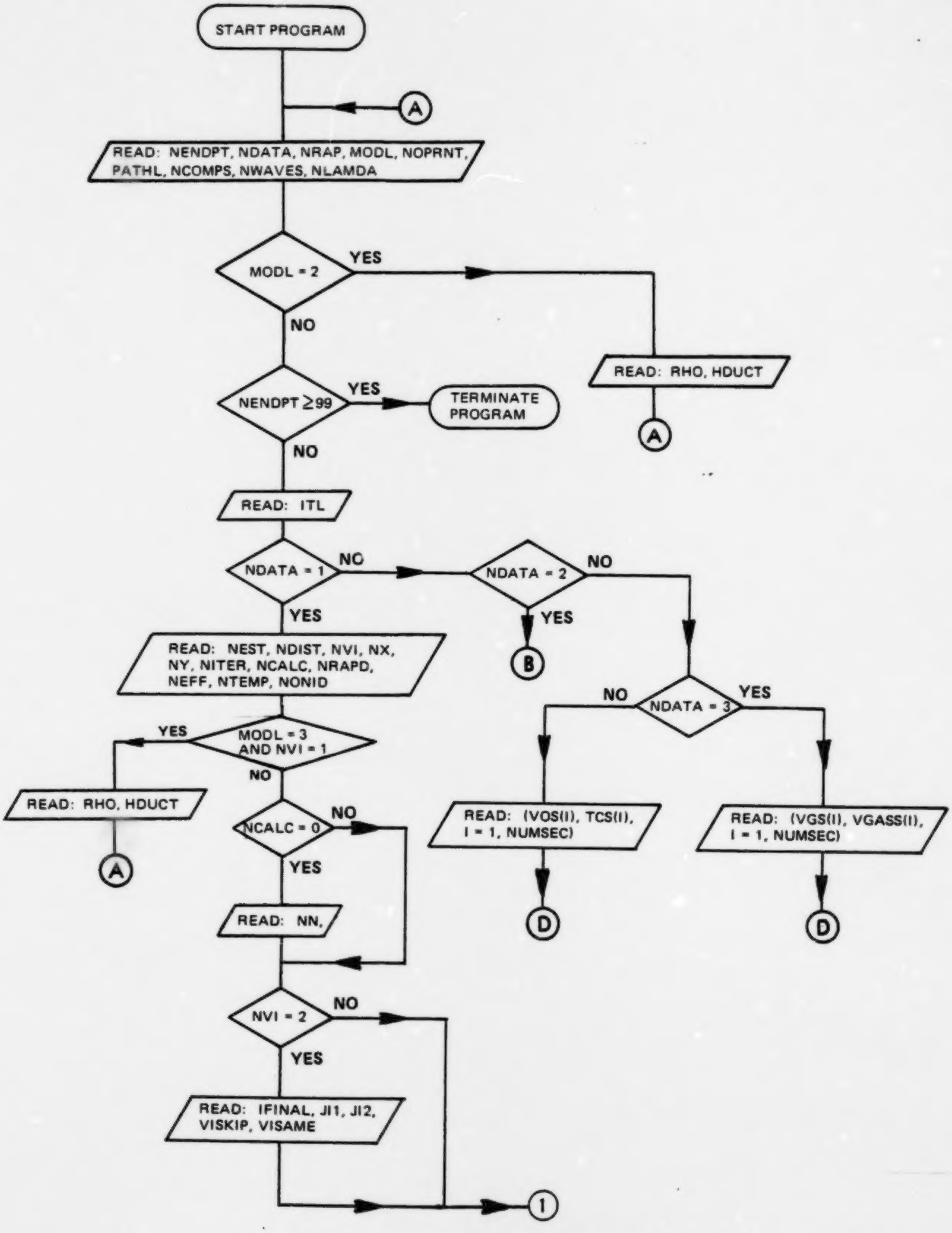

START PROGRAM
A
READ: NENDPT, NDATA, NRAP, MODL, NOPRNT, PATHL, NCOMPS, NWAVES, NLAMDA
MODL = 2
YES
NO
READ: RHO, HDUCT
A
NENDPT ≥ 99
YES
TERMINATE PROGRAM
NO
READ: ITL
NDATA = 1
NO
NDATA = 2
NO
YES
B
YES
READ: NEST, NDIST, NVI, NX, NY, NITER, NCALC, NRAPD, NEFF, NTEMP, NONID
NO
NDATA = 3
YES
YES
MODL = 3 AND NVI = 1
NO
READ: RHO, HDUCT
A
NCALC = 0
NO
YES
READ: NN,
READ: (VOS(I), TCS(I), I = 1, NUMSEC)
D
READ: (VGS(I), VGASS(I), I = 1, NUMSEC)
D
NVI = 2
NO
YES
READ: IFINAL, JI1, JI2, VISKIP, VISAME
1

Figure 34. Flow chart for the input data logic (Sheet 1 of 4).

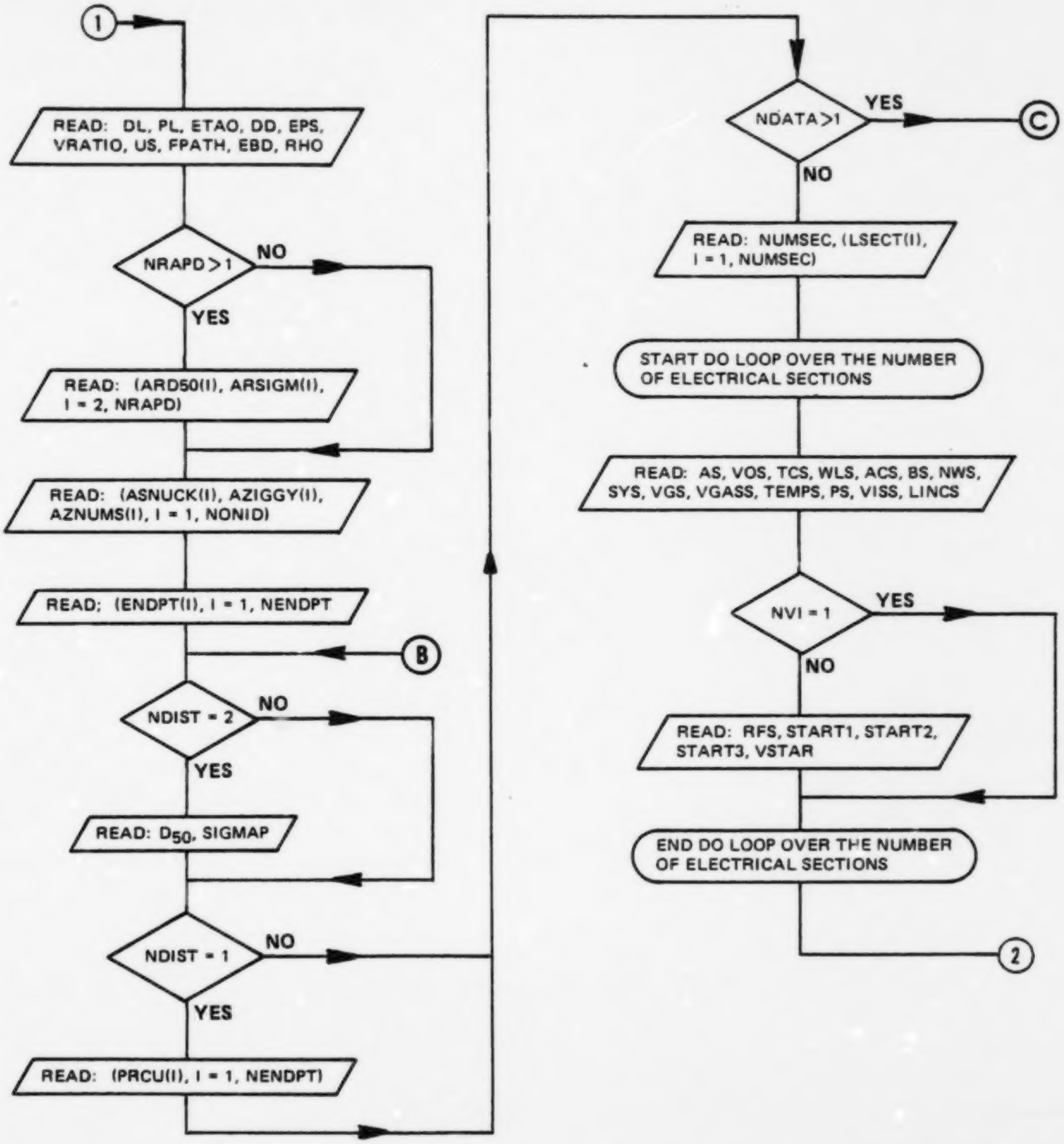

1
READ: DL, PL, ETAO, DD, EPS, VRATIO, US, FPATH, EBD, RHO
NRAPD > 1
NO
YES
READ: (ARD50(I), ARSIGM(I), I = 2, NRAPD)
READ: (ASNUCK(I), AZIGGY(I), AZNUMS(I), I = 1, NONID)
READ; (ENDPT(I), I = 1, NENDPT
B
NDIST = 2
NO
YES
READ: D50, SIGMAP
NDIST = 1
NO
YES
READ: (PRCU(I), I = 1, NENDPT)
NDATA > 1
YES
C
NO
READ: NUMSEC, (LSECT(I), I = 1, NUMSEC)
START DO LOOP OVER THE NUMBER OF ELECTRICAL SECTIONS
READ: AS, VOS, TCS, WLS, ACS, BS, NWS, SYS, VGS, VGASS, TEMPS, PS, VISS, LINCS
NVI = 1
YES
NO
READ: RFS, START1, START2, START3, VSTAR
END DO LOOP OVER THE NUMBER OF ELECTRICAL SECTIONS
2

Figure 34. Flow chart for the input data logic (Sheet 2 of 4).

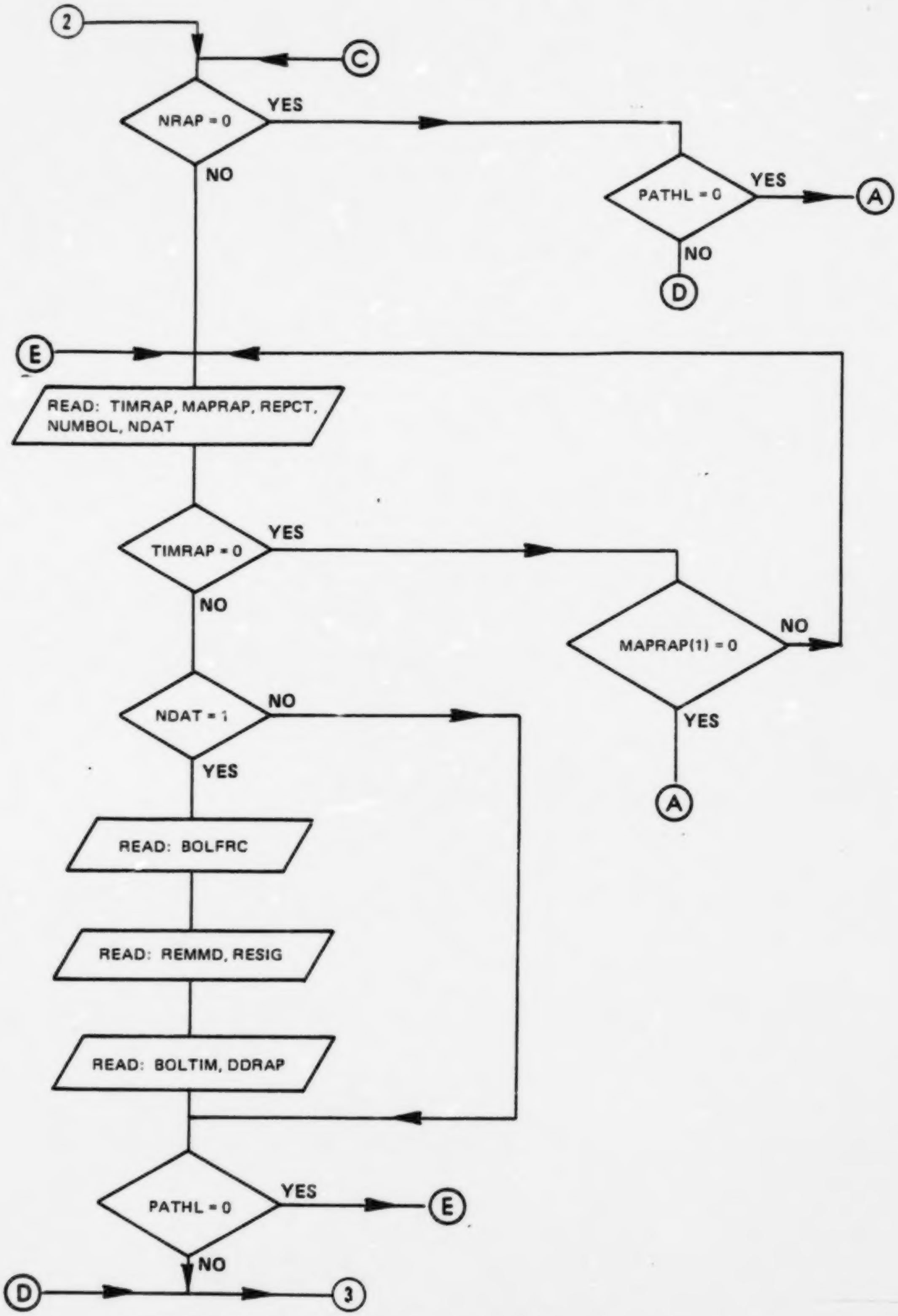

2
C
NRAP = 0
YES
NO
PATHL = 0
YES
A
NO
D
E
READ: TIMRAP, MAPRAP, REPCT, NUMBOL, NDAT
TIMRAP = 0
YES
NO
MAPRAP(1) = 0
NO
YES
A
NDAT = 1
NO
YES
READ: BOLFRC
READ: REMMD, RESIG
READ: BOLTIM, DDRAP
PATHL = 0
YES
E
NO
D
3

Figure 34. Flow chart for the input data logic (Sheet 3 of 4).

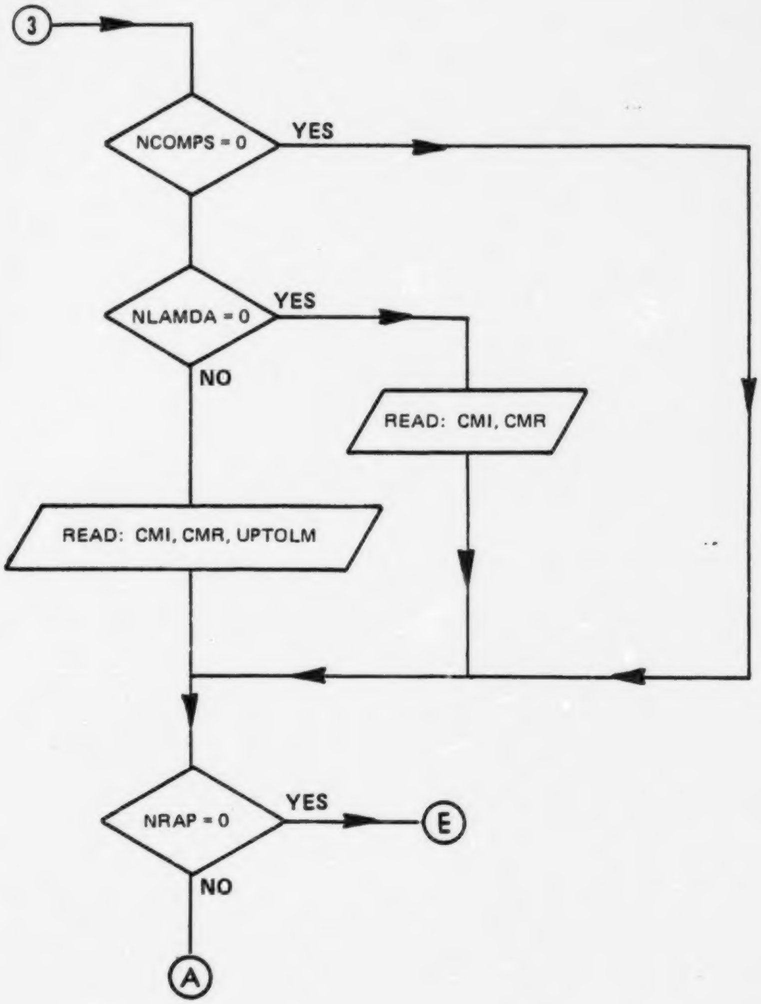

3
NCOMPS = 0
YES
NLAMDA = 0
YES
NO
READ: CMI, CMR
READ: CMI, CMR, UPTOLM
NRAP = 0
YES
E
NO
A

Figure 34. *Flow chart for the input data logic (Sheet 4 of 4).*

(2) NDATA is an indicator which tells the program to look for a certain type of data set. NDATA can have four possible values which will cause the program to look for the following data set types:

1 - A complete data set must be inputted. NDATA must have this value on the first data set.

2 - Only cards 1 and 2 and data concerning size distribution information must be inputted. All other data remain as defined in the previous data set. NDATA can have this value only after a basic data set has been run. This value of NDATA allows one to examine the effects of particle size distribution on precipitator performance with all other variables held fixed.

3 - Only cards 1 and 2 and information concerning the gas volume flow and gas velocity must be inputted. All other data remain as defined in the previous data set. NDATA can have this value only after a basic data set has been run. This value of NDATA allows one to examine the effects of specific collection area (SCA) on precipitator performance with all other variables held fixed.

4 - Only cards 1 and 2 and information concerning the applied voltage and current must be inputted. All other data remain as defined in the previous data set. NDATA can have this value only after a basic data set has been run. This value of NDATA allows one to examine the effects of the electrical conditions on precipitator performance with all other variables held fixed.

NDATA is read in with an I2 format and must be right justified in columns 3-4. If NDATA $\neq$ 1,2,3, or 4, an error message will be given by the computer at the point in the program where NDATA is used in a "computed go to statement". Depending on the particular computer, the program may or may not terminate at this point. If the program continues to execute, it may terminate abnormally at a later point in the program due to incorrect usage of the input data. If the program terminates normally, the calculations may or may not be correct, depending on the input data and the action taken by the computer.

(3) NRAP is an indicator which determines the type of rapping reentrainment correction which will be performed. If NRAP = 0, the correction is performed by the same

empirical process used in the previous versions of this model. If NRAP = 1,2, or 3, a different process is used in which additional data are read into the program. From these data, the particle statistics of the reentrained dust are determined. The program then repeats the efficiency calculation for the input dust plus the reentrained dust, which is introduced into the gas flow at that point in the ESP at which it was rapped loose. The additional data required for dynamic rapping will be described later in this section. The values 1,2, or 3 determine the amount of ESP outlet information which is printed with 1 giving extensive details on individual particle statistics and 3 giving summaries only. These effects are described fully in Section 5 of this report. NRAP is read in with an I2 format and must be right justified in columns 5-6.

(4) MODL is an indicator which specifies the type of data to be read into the program and may have values from 0 to 3. If MODL = 0, mixed British and metric data are to be used. For MODL = 1, all data must be in metric units. If MODL = 2, an internal data set is used and the only other data required from the user is the resistivity of the input particles and the wire to plate spacing. This data set is described later in this section. For MODL = 3, the program terminates after printing the VI curves for the ESP. The options and data sets required when MODL = 3 are described in the subsection on unknown operating conditions. MODL is read in with an I2 format and must be right justified in columns 7-8.

(5) NOPRNT is an indicator which may have the values of 0 or 1. If NOPRNT = 0, the printed output includes data on particle charging and, if opacity is calculated, the differential extinction coefficient for each particle size band. If NOPRNT = 1, particle charging data is not printed and only total opacity figures are printed. NOPRNT is read in with an I2 format and must be right justified in columns 9-10.

(6) PATHL is the path length over which the opacity calculation will be made and is in units of ft or m. PATHL is read in with an F5.2 format in columns 11-15. If PATHL = 0.0, no opacity calculation is performed.

(7) NCOMPS is the number of indices of refraction for which the opacity is to be calculated. NCOMPS may have values from 0 to 10. If NCOMPS = 0 the two default values of the index of refraction are used. These are 1.50 + 0.0i and 1.50 - 0.10i. If NCOMPS = 1 to 10, the calculation is performed for the values which are read

into the program. NCOMPS is read in with an I2 format and must be right justified in columns 19-20.

(8) NWAVES is the number of wavelengths at which opacity will be calculated and may have values of 0 or 1. If NWAVES = 0, the calculation is performed at 10 different points in the spectrum. If NWAVES = 1, the calculation will be performed at a wavelength of 0.55 μm only. NWAVES is read in with an I2 format and must be right justified in columns 24-25.

(9) NLAMDA is the number of indices of refraction which must be read in to perform the opacity calculation using an index of refraction that varies with wavelength. NLAMDA may have values from 0 to 10. If NLAMDA = 0, the index of refraction is assumed to be independent of wavelength and no extra data must be read in. If NLAMDA > 0, then NLAMDA indices of refraction and their associated wavelengths are read into the program. If NLAMDA > 0, NCOMPS must have a value of 1 or 2. If NCOMPS = 0, the value of NLAMDA is ignored. If NCOMPS > 2, and NLAMDA > 0, NCOMPS is set equal to 2. NLAMDA is read with an I2 format and must be right justified in columns 29-30.

The overall format for this group is (5I2, F5.2, 3(3X,I2)). The data contained in this group is on the first card and this card must be the first card in each new data set. However, only the first two parameters, NENDPT and NDATA, are required. The remaining seven parameters are optional. If only the first two parameters are given, the operation of the program is the same as for Revisions I and II except that execution is much faster. Consequently, data sets for the previous version of this model are still usable and will result in the same printed output as before. The use of the optional parameters will result in the inclusion of the extra processes described in the preceding parameter definitions. The last four parameters (PATHL, NCOMPS, NWAVES, and NLAMDA) define the opacity calculation and are interrelated as shown in Table 3.

Data group 2 is for specifying information which will identify the data set which is under consideration. All or part of columns 1-80 on data card 2 can be used in identifying the data set. The overall format for this card is (40A2). This data group must be the second card in each new data set.

At this point, the third and successive data groups depend on the choice of the value of NDATA. The basic data set must be read into the program before shortened data sets can be used. For NDATA=1, the program reads in the data groups in the basic data set in the sequence discussed below.

TABLE 3. OPACITY RELATED INPUT DATA

	VALUE OF PARAMETER			
PATHL	NCOMPS	NWAVES	NLAMDA	CALCULATIONS PERFORMED
0.	--	--	--	No opacity calculation performed
>0	0	0	--	Opacity calculated at 10 wavelengths using default values of index of refraction
>0	0	1	--	Opacity calculated at 1 wavelength using default values of index of refraction
>0	1,2	0	0	Opacity calculated at 10 wavelengths using NCOMPS user supplied values of index of refraction
>0	1 to 10	1	0	Opacity calculated at 1 wavelength using NCOMPS user supplied values of index of refraction
>0	1,2	0	1 to 10	Opacity calculated at 10 wavelengths using NLAMDA user supplied values of frequency dependent index of refraction

The following is a sequential listing of the variables in data group 3, along with the descriptions of the variables and the format specifications.

(1) NEST is an indicator which can have the values of 1 and 2. If NEST = 1, the program will perform extensive, detailed calculations in order to determine precipitator performance. If NEST = 2, estimation procedures are used to determine precipitator performance. Both of these options have been discussed in detail in Section 6. Use of the estimation procedure will result in considerable savings in computer time and can be used to establish trends or to establish ranges over which to apply the more rigorous calculations. NEST is read in with an I2 format and must be right justified in columns 1-2.

(2) NDIST is an indicator which can have the values of 1 and 2. If NDIST = 1, the user must supply the inlet particle size distribution corresponding to the size bands specified by the variable ENDPT. If NDIST = 2, the program will construct a log-normal particle size distribution for these size bands based on the parameters D50 and SIGMAP. The technique used to construct the log-normal size distribution is described in Section 7. NDIST is read in with an I2 format and must be right justified in columns 3-4.

(3) NVI is an indicator which can have the value 1 or 2. If NVI = 1, the user must supply known or measured values of the operating applied voltage and current. If NVI = 2, the program will construct a voltage-current curve (or curves) for a specified wire-plate geometry up to a voltage which is specified by the user. Refer to the subsection on unknown operating conditions to determine when this option should be used. NVI is read in with an I2 format and must be right justified in columns 5-6.

(4) NX is the number of grid points in the x-direction (perpendicular to the gas flow) which is used in the numerical techniques that determine the electrical conditions. NX cannot exceed a value of 15. If NVI = 1, sufficient accuracy can normally be obtained with NX $\geq$ 11. If NVI = 2, NX should be set equal to 15. NX is read in with an I2 format and must be right justified in columns 7-8.

(5) **NY** is the number of grid points in the y-direction (parallel to the gas flow) which is used in the numerical techniques that determine the electrical conditions. If NVI = 1, sufficient accuracy can normally be obtained with NY $\geq$ 9. If NVI = 2, NY should be set equal to 15. NY is read in with an I2 format and must be right justified in columns 9-10.

(6) **NITER** is an indicator which serves two different purposes. If NVI = 1, the value of NITER determines the maximum number of iterations the program will make on a loop which converges on overall mass collection efficiency. If the overall mass collection efficiency converges within 0.05% before NITER iterations, the calculation of collection efficiencies is completed at this point. NITER serves the purpose of cutting the calculation off in a reasonable amount of time when convergence requires more iterations and computer time than is warranted. For normal inlet mass loadings and particle size distributions a value of NITER = 2 is sufficient. For high inlet mass loadings or very fine particle size distributions a value of NITER = 3 or 4 may be necessary to provide sufficient accuracy. If NVI = 2, the value of NITER determines the number of iterations which will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions. In its present stage of development, the calculation procedure yields the same results for all values of NITER. Thus, in this case, set NITER = 1. The calculation procedure is discussed in Appendix A. NITER is read in with an I2 format and must be right justified in columns 11-12.

(7) **NCALC** is an indicator which can have the values of 0 and 1. If NCALC = 0, particle charge is determined by using equation (12). Due to the number of times particle charge must be calculated and the use of numerical techniques in order to solve the charging equation, the particle charging calculations for NCALC = 0 take a considerable amount of computer time. If NCALC = 1, particle charge is estimated empirically by using the sum of the charges predicted from classical field and thermal charging theories [see equation (15)]. In this case, particle charge can be determined very rapidly from analytical expressions. Thus, in those cases where a significantly shorter run time is more important than the best accuracy possible, NCALC should be set equal to 1. If NEST = 2, particle charge will be performed as if NCALC = 1 regardless of the value of NCALC. NCALC is read in with an I2 format and must be right justified in columns 13-14.

(8) NRAPD is an indicator which specifies the number of rapping puff particle size distributions which will be utilized by the program in predicting the effect of rapping reentrainment on overall mass collection efficiency. NRAPD must have a value of at least 1 and can not exceed a value of 10. If NRAPD = 1, the program will determine the rapping puff particle size distribution based on the average of data obtained from several field tests on full-scale precipitators. These tests yield an average rapping puff particle size distribution with a mass median diameter (MMD) of 6.0 μm and a geometric standard deviation (σ_p) of 2.5. The technique which is used to predict rapping losses is discussed in Volume 1. If NRAPD is greater than one, the user must supply a MMD and σ_p of a log-normal distribution corresponding to each value of NRAPD greater than 1. The program will determine the rapping puff particle size distribution based on the specified combinations of MMD and σ_p. The case for NRAPD = 1 will always be performed. Each rapping puff particle size distribution is used in conjunction with the same basic ideal calculation and its effect is determined with very little expenditure of computer time. NRAPD is read in with an I2 format and must be right justified in columns 15-16.

(9) NEFF is an indicator which can have the values of 1 and 2. If NEFF = 1, the total mass reentrained at the outlet due to rapping is determined from the mass collected in the last field under adjusted no-rap conditions. If NEFF = 2, the total mass reentrained at the outlet due to rapping is determined from the mass which would be collected in the last field under unadjusted ideal conditions. NEFF should normally be taken to be 1 since this case is physically meaningful. A value of NEFF = 2 will result in rapping losses which are significantly greater than for NEFF = 1. Thus, a value of NEFF = 2 should only be used when a precipitator design which is conservative with respect to rapping losses is desired. NEFF is read in with an I2 format and must be right justified in columns 17-18.

(10) NTEMP is an indicator which can have the values of 1 and 2. The mass reentrained due to rapping will differ for cold-side and hot-side precipitators. If NTEMP = 1, the mass reentrained due to rapping is estimated based on an equation for cold-side precipitators. If NTEMP = 2, the mass reentrained due to rapping is estimated based on equation for hot-side precipitators. NTEMP is read in with an I2 format and must be right justified in columns 19-20.

(11) NONID is an indicator which specifies the number of combinations of normalized gas velocity standard deviation (σ_g) and gas bypassage fraction and/or particle reentrainment fraction without rapping (S) which are to be used to simulate the possible nonideal conditions. The procedures used to account for these nonideal effects are described in Volume 1. NONID must have a value of at least 1 and can not exceed a value of 15. Each set of nonideal conditions is used in conjunction with the same basic ideal calculation and its effect is determined with very little expenditure of computer time. NONID is read in with an I2 format and must be right justified in columns 21-22.

The overall format for this data group is (11I2) and all the data are contained on the third data card.

The next data group which is read in depends on the values of NCALC and NVI. If NCALC = 0, the rigorous charging theory is used. In this case, the following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) NN is the number of increments in the Runge-Kutta integration of equation (12). A value of NN = 5 will provide sufficient accuracy for normal use. Greater values found in data sets created for previous versions of the model may be used but will result in an increase in computer time for no appreciable increase in accuracy. NN is read in with an I2 format and must be right justified in columns 1-2.

(2) NUMINC was previously the number of increments in the Simpson's Rule integration over θ in equation (12). Since this integration is now done by the Gaussian Quadrature method, this variable is no longer used. Data sets containing this variable may still be used, however, as the space allocated to NUMINC, columns 3-4, is not used for any other purpose.

The overall format for this data group is (I2) and all the data are contained on a single card. If NCALC = 1, the above data group is not read into the program.

If NVI = 2, the model must calculate a voltage-current curve. In this case, the following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) IFINAL is an indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points. This indicator allows the user to have the V-I calculation terminated at a point before the specified operating voltage is reached whenever it is taking an excessive number of points to reach the specified operating voltage. IFINAL is read in with an I2 format and must be right justified in columns 1-2.

(2) JI1 is an indicator which allows the initial increment size on current density in the calculation of the voltage-current curve to be changed after JI1-1 points are determined on the curve. Since the voltage-current calculation finds the applied voltage corresponding to a specified value of current density, this indicator allows the user to cover a large range of current densities without using an excessive number of points. JI1 is read in with an I2 format and must be right justified in columns 3-4.

(3) JI2 is an indicator which allows the second increment size on current density in the calculation of the voltage-current curve to be changed after JI2-1 points are determined on the curve. JI2 serves the same function as JI1 and JI2 must have a value greater than JI1 for proper usage. JI2 is read in with an I2 format and must be right justified in columns 5-6.

(4) VISKIP is an indicator which may have the values of 0 and 1. If VISKIP = 0, a voltage-current curve will be calculated up to a specified operating voltage for each successive length increment of the precipitator. If VISKIP = 1, only the operating current density which corresponds to a specified operating voltage will be calculated based on an estimation procedure discussed in Volume 1. In most cases, the user will want to set VISKIP = 1 since this will result in a prediction of the operating current density in each increment of length of the precipitator without using the large amounts of computer time required by the calculation of a voltage-current curve. Only extremely detailed analysis would warrant setting VISKIP = 0. VISKIP is read in with an I2 format and must be right justified in columns 7-8.

(5) VISAME is an indicator which may have the values of 1 and 2. The proper use of VISAME can result in significant savings in computer time whenever the applied voltage is the same in each electrical section. If the applied voltage is the same in each electrical section, set VISAME = 1 and only one "clean" voltage-current curve

will be calculated. If VISAME = 1, as many data sets as desired can be read into the program and all calculations will be based on the one "clean" voltage-current calculation. The use of VISAME = 1 is especially beneficial in studying hypothetical cases due to the large savings in computer time. If the applied voltage differs from one electrical section to the next, the user must set VISAME = 2. Whenever the operating voltage and current are unknown and the user must specify the use of the voltage-current calculations (NVI = 2), the quickest run time will occur when VISKIP = 1 and VISAME = 1. The longest run time will occur when VISKIP = 0 and VISAME = 2. VISAME is read in with an I2 format and must be right justified in columns 9-10.

The overall format for this data group is (5I2) and all data are contained on a single card. If NVI = 1, the above data group is not read into the program.

The following is a sequential listing of the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) DL is the inlet particulate mass loading in units of grains/ft^3 or kg/m^3. DL is read in with a F8.0 format and must be left justified in columns 1-8.

(2) PL is the total electrical length of the precipitator in units of ft or m. PL is read in with a F8.0 format and must be left justified in columns 9-16.

(3) ETAO is the overall mass collection efficiency in units of percent and it has two different interpretations depending upon the value of NVI. If NVI = 1, ETAO represents the measured or estimated overall mass collection efficiency and is used as a test for convergence in an iteration loop on overall mass collection efficiency. If NVI = 2, ETAO simply represents the desired design efficiency and is not used in the calculations. ETAO is read in with a F8.0 format and must be left justified in columns 17-24.

(4) DD is the density of the particles in units of kg/m^3. DD is read in with a F8.0 format and must be left justified in columns 25-32.

(5) EPS is the dielectric constant of the particles for use in the particle charging calculations and is dimensionless. Values of EPS must be equal to or greater than 1. In most industrial applications, the flue gas is sufficiently humidified so that the particle surface becomes conductive and a value of EPS = 100 can be used to simulate

a conductor. EPS is read in with a F8.0 format and must be left justified in columns 33-40.

(6) VRATIO is the ratio of the peak voltage to the average voltage and is dimensionless. In the calculation of particle charge, it is assumed that the particles will charge to an extent determined by the peak voltage rather than the average voltage. For industrial applications, VRATIO has a value around 1.2. VRATIO is read in with a F8.0 format and must be left justified in columns 41-48.

(7) US is the ionic mobility at standard temperature (273°K) and standard pressure (1 atm) and is in units of $m^2/(V\text{-}sec)$. This mobility is referred to as the "reduced mobility". Values to use for reduced ionic mobilities for flue gas compositions are not well-established at the present time. The reduced ionic mobility for air is in the range $1.2\text{-}2.1 \times 10^{-4} m^2/(V\text{-}sec)$. Reduced ionic mobilities for flue gas compositions have been reported that are considerably larger than those reported for air. These values cover the range of $2.2\text{-}5.4 \times 10^{-4} m^2/(V\text{-}sec)$. Some reported values of reduced ionic mobility for various gas compositions are given in Table 4. Since the ionic mobility has a strong influence on the electrical conditions through the current and electric field distributions, this is an important parameter in determining precipitator performance. A value of $2.7 \times 10^{-4} m^2/(V\text{-}sec)$ should provide a representative value to use for flue gases emanating from coal-fired boiler applications. US is read in with a F8.0 format and must be left justified in columns 49-56.

(8) FPATH is a parameter which is used in the field charging equation and is dimensionless. FPATH represents the number of ionic mean free paths over which the momentum of the ions will persist and allow the ions to reach the surface of the particle even though the saturation charge has been reached. The effect of this parameter is to increase the saturation charge. FPATH normally should have a value in the range 0-2. It is recommended that FPATH be assigned a value of 1. FPATH is read in with a F8.0 format and must be left justified in columns 57-64.

(9) EBD is the electrical breakdown strength of the gas or the particulate layer in the region near the plate and is in units of V/m. The value of this parameter is a strong function of the resistivity of the collected

TABLE 4

REDUCED EFFECTIVE NEGATIVE ION MOBILITIES FOR VARIOUS GAS COMPOSITIONS

Gas Composition (Volume Percent)					Reduced Effective Ion Mobility (cm^2/V-sec)
N_2	CO_2	O_2	SO_2	H_2O	
				100.0	0.67 ± 0.17[a]
		100.0			2.46 ± 0.06[b]
	100.0				1.08 ± 0.03[b]
			100.0		0.35[c]
	(Laboratory Air)				1.03[d]
	(Laboratory Air)				1.26 - 1.96[e]
79.4	14.7	4.6	0.2	0.6	5.39[f]
73.5	13.6	4.2	0.2	8.4	2.93[f]
65.9	12.2	3.8	0.2	17.8	2.23[f]
71.0	11.2	3.7	0.0	14.0	2.35[f]
75.7	11.6	3.2	0.0	9.4	3.02[f]
75.1	11.5	3.2	0.1	9.9	2.74[f]
78.5	10.9	3.6	0.0	7.0	3.36[f]
78.3	19.8	3.6	0.1	7.0	2.67[f]
77.9	10.8	3.6	0.3	7.0	2.70[f]
77.6	10.7	3.7	0.7	7.0	2.43[f]

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a. J. J. Lowke and J. A. Rees, Australian J. Phys. 16, 447 (1963).

b. E. W. McDaniel and H. R. Crane, Rev. Sci. Instru. 28, 684 (1959).

c. E. W. McDaniel and M. R. C. McDowell, Phys. Rev. 114, 1028 (1959).

d. B.Y.H. Liu, K. T. Whitby, and H.H.S. Yu, J. Appl. Phys. 38, 1592 (1967).

e. J. Bricard, M. Cabane, G. Modelaine, and D. Vigla, Aerosols and Atmospheric Chemistry. Edited by G. M. Hidy, New York, New York, 27 (1972).

f. H. W. Spencer, III, "Experimental Determination of the Effective Ion Mobility of Simulated Flue Gas." In Proceedings of 1975 IEEE-IAS Conference, September 28, 1975, Atlanta, Georgia.

particulate layer and the condition of the collection plates. At present, mathematical techniques which are based on physical principles do not exist for predicting the value of EBD under differing conditions. Thus, experimental data and prior experience must be used to choose appropriate values of EBD. In practical applications, EBD falls in the range of 2-15 kV/cm. A value of 2 kV/cm should provide a conservative estimate of EBD whereas a value of 15 kV/cm would in most cases provide the most optimistic value. The value of EBD is used whenever NVI = 2 and a voltage-current curve is generated. If the field at the plate exceeds the value of EBD at any point on the curve, a message to this effect is printed out with the V-I calculation terminating at the corresponding applied voltage and current density. These values of voltage and current are then used in the projection of precipitator performance. EBD is read in with a F8.0 format and must be right justified in columns 65-72.

(10) RHO is the resistivity of the collected particulate layer and is in units of ohm-cm. The resistivity to be used must be determined experimentally by either in situ or laboratory methods. RHO is used in the model only if the operating conditions are unknown. For this use refer to the subsection on unknown operating conditions. RHO is read in with an 8.2 format and must be right justified in columns 73-80.

> When the operating voltages and current are specified, the value of RHO has no effect on the operating conditions. To estimate the effects of a change in RHO, the procedures listed under unknown operating conditions must be used.

The above data group has an overall format of (9F8.0, E8.2) and is contained on a single data card. This data set must be read in with each basic data set, i.e. when NDATA = 1.

The next data group which is read in depends on the value of NRAPD. If NRAPD is greater than 1, the following is a sequential listing of the variables in the next data group, along with the descriptions of the variables and the format specifications.

(1) ARD50(I) is an array containing the mass median diameters in μm for log-normal particle size distributions of the different rapping puff distributions which will be utilized in the model. The values of this variable are read in with a F4.0 format and must be left justified in columns 1-4, 9-12, 17-20, 25-28, 33-36, 41-44, 49-52, 57-60, 65-68, and 73-76.

(2) ARSIGM(I) is an array containing the geometric standard deviations for log-normal particle size distributions of the different rapping puff distributions which will

be utilized in the model. Values of ARD50(I) and ARSIGM(I) with the same index are used together to construct a log-normal particle size distribution. The values of this variable are read in with a F4.0 format and must be left justified in columns 5-8, 13-16, 21-24, 29-32, 37-40, 45-48, 53-56, 61-64, 69-72, and 77-80. ARSIGM(I) can not have a value less than 1.

The above variables must be read in for I=2 up to I=NRAPD where NRAPD can not exceed a value of 10. The overall format for this data group is (10(2F4.0)) and is contained on a single data card. If NRAPD=1, this data group is not read in. In this case, only one rapping puff particle size distribution will be considered where ARD50(1) = 6.0 in μm and ARSIGM(1) = 2.5. This case is built into the program and relates to experimental data discussed in Section 6.

The following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) ASNUCK(I) is an array containing different fractions of gas flow which bypass the electrified region in each baffled stage of the precipitator and/or different fractions of the mass collected in each stage of the precipitator which are reentrained due to factors other than rapping. The values of this variable are read in with a F4.0 format and must be left justified in columns 1-4, 13-16, 25-28, 37-40, 49-52, and 61-64 of the first two data cards in the group and in columns 1-4, 13-16, and 25-28 of the third data card in the group. ASNUCK(I) must lie in the range 0.0 to 1.0.

(2) AZIGGY(I) is an array containing different normalized standard deviations for the inlet velocity distribution of the gas flow. The values of this variable are read in with a F4.0 format and must be left justified in columns 5-8, 17-20, 29-32, 41-44, 53-56, and 65-68 of the first two data cards in the group and in columns 5-8, 17-20, and 29-32 of the third data card in the group. AZIGGY(I) must be equal to or greater than 0.0.

(3) AZNUMS(I) is an array containing the number of baffled stages in the precipitator. The values of this variable are read in with a F4.0 format and must be left justified in columns 9-12, 21-24, 33-36, 45-48, 57-60, and 69-72 of the first two data cards in the group and in columns 9-12, 21-24, and 33-36 of the third data card in the group. The values of AZNUMS(I) must be whole numbers.

The values of ASNUCK(I), AZIGGY(I), and AZNUMS(I) with the same index are used together to simulate one set of nonideal parameters and to produce one set of no-rap efficiencies. The values of I are determined by NONID which must have a value of at least 1 and can not exceed a value of 15. Thus, at least one set of these parameters must be read in. It is recommended that the user take the first set of these variables to be ASNUCK(1) = 0.00, AZIGGY(1) = 0.00, and AZNUMS(1) = actual number of stages so that efficiencies under ideal conditions will be obtained. In practical situations, a well-operating precipitator will have values of ASNUCK and AZIGGY of approximately 0.1 and 0.25, respectively.

The overall format for this data group is (6(3F4.0)) and the data group is contained on 3 or less cards. For NONID ≤ 6, 6<NONID ≤ 12, and 12<NONID ≤ 15, the number of data cards necessary are 1, 2, and 3, respectively. This data group must be read in with each basic data set.

The next data group which is read in consists of a single array. The description of this array and its format specification are given below.

(1) ENDPT(I) is an array containing values of particle diameters corresponding to points on a curve of inlet mass cumulative percent versus particle diameter. The number of diameters read in must equal the value of NENDPT which can not exceed a value of 21. The diameters must be inputted in order from smallest to largest in units of μm. The smallest diameter can not be less than 0.01 μm and the largest diameter can not exceed 1,000 μm. These diameters are used to construct particle size intervals and a particle size histogram. The midpoints between successive particle diameters constitute NENDPT-1 average particle diameters which are used in the program to characterize the different particle size bands. In constructing the particle diameters to be used in the calculations, it is recommended that greater resolution be built into the fine particle size range of 0.1-3.0 μm since the lower efficiencies are obtained in this size range. The values of ENDPT(I) are read in with a F8.0 format and must be left justified.

The overall format for this data group is (10F8.0) and the data group is contained on 3 or less data cards. For NENDPT ≤ 10, 10<NENDPT ≤ 20, and NENDPT = 21, the number of data cards necessary are 1, 2, and 3, respectively. This data group must be read in with each basic data set.

The next data group which is read in depends on the value of NDIST. If NDIST = 2, the following is a sequential listing of the variables in the next data group, along with the descriptions of the variables and the format specifications.

(1) D50 is the mass median diameter of a log-normal inlet particle size distribution and is in units of μm. The value of D50 must lie between 0.01 and 1,000 μm. The value of D50 is read in with a F8.0 format and must be left justified in columns 1-8.

(2) SIGMAP is the geometric standard deviation of a log-normal inlet particle size distribution and is dimensionless. The value of SIGMAP must be equal to or greater than 1. The value of SIGMAP is read in with a F8.0 format and must be left justified in columns 9-16.

The program uses the values of D50 and SIGMAP to construct a log-normal particle size distribution over the range and size bands determined by the values of ENDPT(I). Any mass which is not in the size range determined by ENDPT(I) will be put into the size band with the largest midpoint. This must be done to ensure that the sum over all size bands of the percentage of total mass in each size band will equal 100%.

The above data group has an overall format of (2F8.0) and is contained on a single data card. This data set is not read in if NDIST = 1.

If NDIST = 1, the next data group which is read in consists of a single array. The description of this array and its format specification are given below.

(1) PRCU(I) is an array containing values of cumulative percents corresponding to points on a curve of inlet mass cumulative percent versus particle diameter. The number of cumulative percents read in must equal the value of NENDPT which can not exceed 21. The cumulative percents must match the particle diameters specified in the array ENDPT(I). The cumulative percents are entered in units of %. The first value of PRCU(I) must be 0% and the last value must be 100%. The program determines the percentage by mass in each particle size band from the values contained in ENDPT(I) and PRCU(I). The user must supply values of PRCU(I) based on measured or known particle size information for the particular application under consideration. The values of PRCU(I) are read in with a F8.0 format and must be left justified.

The overall format for this data group is (10F8.0) and the data group is contained on 3 or less data cards. For NENDPT $\leq$ 10, 10<NENDPT $\leq$ 20, and NENDPT = 21, the number of data cards necessary are 1, 2, and 3, respectively. This data group is not read in if NDIST = 2.

The following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) NUMSEC is the number of electrical sections in the direction of gas flow. The maximum number of electrical sections which can be accounted for in the program listed in Appendix C is 10. The value of this variable is read in with an I2 format and must be right justified in columns 1-2.

(2) LSECT(I) is an array containing values of the number of incremental lengths to be taken in each electrical section in the direction of gas flow. These values are determined by the user with increasing values of I corresponding to electrical sections moving from the inlet to the outlet of the precipitator. The total number of incremental lengths in all sections must not exceed 99. It is not necessary to have the same number in each section. The values of this variable are read in with an I2 format and must be right justified.

The overall format for this data group is (I2, 10I2) and the data group is contained on a single data card. This data group must be read in with each basic data set.

The following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) AS(NSECT) is the total collection plate area for a given electrical section and is in units of ft^2 or m^2. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11.

(2) VOS(NSECT) is the applied voltage in a given electrical section and is in units of volts. If NVI = 1, the value of VOS(NSECT) corresponds to a measured or known value. If NVI = 2, VOS(NSECT) corresponds to an applied voltage up to which a voltage-current curve will be calculated. Then, this applied voltage

along with the corresponding current will be used in the calculation of precipitator performance. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22.

(3) TCS(NSECT) is the total current in a given electrical section and is in units of amperes. If NVI = 1, the value of TCS(NSECT) corresponds to a measured or known value. If NVI = 2, TCS(NSECT) has no meaning in terms of input data since it will be calculated in the program. In this case, the appropriate columns on the data card can be left blank or any arbitrary number can be entered. The values of this variable are read in with an E11.4 format and must be right justified in columns 23-33.

(4) WLS(NSECT) is the total effective wire length in a given electrical section and is in units of ft or m. The values of this variable are read in with an E11.4 format and must be right justified in columns 34-44.

(5) ACS(NSECT) is the corona wire radius in a given electrical section and is in units of in. or mm. The values of this variable are read in with an E11.4 format and must be right justified in columns 45-55.

(6) BS(NSECT) is the wire-to-plate spacing in a given electrical section and is in units of in. or m. The values of this variable are read in with an E11.4 format and must be right justified in columns 56-66.

(7) NWS(NSECT) is the number of discharge electrodes per given electrical section per gas passage and is dimensionless. The values of this variable normally should not exceed 20. If the values do exceed 20, use 20 in the program. These values are used to determine the number of terms in a series summation which determines the electrostatic electric field distribution and 20 terms are more than sufficient to reach convergence. The values of this variable are read in with an E11.4 format and must be right justified in columns 67-77.

(8) SYS(NSECT) is one-half of the wire-to-wire spacing in a given electrical section and is in units of in. or m. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11.

(9) VGS(NSECT) is the total gas volume flow rate in a given electrical section and is in units of actual ft^3/min or m^3/sec. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22.

(10) VGASS(NSECT) is the gas velocity in a given electrical section and is in units of ft/sec or m/sec. The values of this variable are read in with an E11.4 format and must be right justified in columns 23-33. The gas velocity must be consistent with the gas volume flow rate and the precipitator geometry in each electrical section. These are related by

$$VGASS(I) = (LINCS(I)*LSECT(I)*VGS(I))/(AS(I)*BS(I)*Constant), \quad (111)$$

where the constant = 1 for metric units and 5 for English units.

(11) TEMPS(NSECT) is the gas temperature in a given electrical section and is in units of °F or °C. The values of this variable are read in with an E11.4 format and must be right justified in columns 34-44.

(12) PS(NSECT) is the gas pressure in a given electrical section and is in units of atmospheres. The values of this variable are read in with an E11.4 format and must be right justified in columns 45-55.

(13) VISS(NSECT) is the gas viscosity in a given electrical section and is in units of kg/(m-sec). Table 5 gives values of viscosity for different temperatures and water contents for a gas composition whose components are those of air. This table provides values of viscosity which cover most cases found in practice although some extrapolation is necessary for those cases involving hot precipitators where temperatures are greater than 300°C. The values of this variable are read in with an E11.4 format and must be right justified in columns 56-66.

(14) LINCS(NSECT) is the incremental length size which will be taken in a given electrical section and is in units of ft or m. If NVI = 1, LINCS(NSECT) should be given a value of approximately one foot although larger values can be used with some loss in accuracy in order to save computer run time. If NVI = 2, LINCS(NSECT) must be given a value equal as near as possible to the wire-to-wire spacing in order for the numerical procedure to be valid. In any case, the product of LSECT(NSECT) and LINCS(NSECT) must equal the total length of the given electrical section. The values of this variable are read in with an E11.4 format and must be right justified in columns 67-77.

The overall format for this data group is (7(E11.4)) and the data group is contained on two data cards. This data group must be read in with each basic data set.

TABLE 5. VALUES OF VISCOSITY FOR AIR AT VARIOUS TEMPERATURES AND WATER CONTENTS*

	Percent H_2O										
°C	0	1	2	3	4	5	6	7	8	9	10
10	1.767	1.758	1.748	1.739	1.730	1.721	1.712	1.702	1.693	1.684	1.675
20	1.810	1.801	1.792	1.783	1.774	1.765	1.755	1.746	1.737	1.728	1.719
30	1.854	1.844	1.835	1.826	1.817	1.808	1.799	1.790	1.780	1.771	1.762
40	1.900	1.887	1.878	1.869	1.860	1.850	1.841	1.832	1.823	1.814	1.805
50	1.938	1.929	1.920	1.911	1.902	1.892	1.883	1.874	1.865	1.856	1.847
60	1.979	1.970	1.961	1.952	1.943	1.934	1.925	1.916	1.907	1.898	1.888
70	2.020	2.011	2.002	1.993	1.984	1.975	1.966	1.957	1.948	1.939	1.930
80	2.059	2.050	2.042	2.033	2.024	2.015	2.006	1.997	1.988	1.979	1.970
90	2.099	2.090	2.081	2.072	2.063	2.054	2.046	2.037	2.028	2.019	2.010
100	2.137	2.129	2.120	2.111	2.102	2.093	2.085	2.076	2.067	2.058	2.049
110	2.175	2.167	2.158	2.149	2.140	2.132	2.123	2.114	2.105	2.097	2.088
120	2.213	2.204	2.195	2.189	2.178	2.169	2.161	2.152	2.143	2.135	2.126
130	2.250	2.241	2.232	2.224	2.215	2.207	2.198	2.189	2.181	2.172	2.164
140	2.286	2.277	2.269	2.260	2.252	2.243	2.235	2.226	2.218	2.209	2.201
150	2.321	2.313	2.304	2.296	2.288	2.279	2.271	2.262	2.254	2.245	2.237
160	2.356	2.348	2.339	2.331	2.323	2.315	2.306	2.298	2.289	2.281	2.273
170	2.390	2.382	2.374	2.366	2.358	2.349	2.341	2.333	2.325	2.316	2.308
180	2.424	2.416	2.408	2.400	2.392	2.383	2.375	2.367	2.359	2.351	2.343
190	2.457	2.449	2.441	2.433	2.425	2.417	2.409	2.401	2.393	2.385	2.377
200	2.489	2.482	2.474	2.466	2.458	2.450	2.442	2.434	2.426	2.418	2.410
210	2.521	2.513	2.506	2.498	2.490	2.482	2.475	2.467	2.459	2.451	2.443
220	2.552	2.545	2.537	2.530	2.522	2.514	2.507	2.499	2.491	2.483	2.476
230	2.583	2.575	2.568	2.560	2.553	2.545	2.538	2.530	2.523	2.515	2.507
240	2.613	2.606	2.598	2.591	2.583	2.576	2.569	2.561	2.554	2.546	2.539
250	2.642	2.635	2.628	2.621	2.613	2.606	2.599	2.592	2.584	2.577	2.570
260	2.671	2.664	2.657	2.650	2.643	2.636	2.628	2.621	2.614	2.607	2.600
270	2.699	2.692	2.685	2.678	2.671	2.664	2.657	2.650	2.643	2.636	2.629
280	2.727	2.720	2.713	2.706	2.700	2.693	2.686	2.679	2.672	2.665	2.658
290	2.754	2.747	2.740	2.734	2.727	2.720	2.714	2.707	2.700	2.694	2.687
300	2.780	2.773	2.767	2.761	2.754	2.748	2.741	2.734	2.728	2.721	2.715

X 10^{-5} kg/(m-sec)

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*Calculations according to:
C.R. Wilke. A Viscosity Equation for Gas Mixtures. J. Chem. Phy., 18(4):517-519 (April, 1950).

The next data group which is read in depends on the value of NVI. If NVI = 2, the following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) RFS(NSECT) is the roughness factor for the wires in a given electrical section and is dimensionless. In precipitation practice, if the wires are scratched or dirty but not completely coated with air, then the values of RFS(NSECT) lie in the range 0.5-1.0. A value of 1.0 corresponds to wires which are in perfect condition. The effect of decreasing the roughness factor is one of increasing the current that can be achieved at a given voltage level. If the wires are completely covered with dirt, then the effect may be one of increased wire diameter with a roughness superimposed. This situation would lead to compensating effects. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11.

(2) START1(NSECT) is the chosen initial current density at which the calculation of a voltage-current curve starts in a given electrical section and is in units of A/m^2. In generating the voltage-current curve, the current density increments in steps of START1 (NSECT) until a change is specified. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22.

(3) START2(NSECT) is a chosen increment in current density which is used in place of START1(NSECT) when the JI1-th point on the voltage-current curve is reached and is in units of A/m^2. The values of this variable are read in with an E11.4 format and must be right justified in columns 23-33.

(4) START3(NSECT) is a chosen increment in current density which is used in place of START2(NSECT) when the JI2-th point on the voltage-current curve is reached and is in units of A/m^2. The values of this variable are read in with an E11.4 format and must be right justified in columns 34-44.

(5) VSTAR(NSECT) is an estimate of the applied voltage corresponding to the first point on the voltage-current curve as defined by START1(NSECT) and is in units of volts. If VSTAR(NSECT) is close to the actual applied voltage, the calculation will be performed faster. However, whatever the choice of VSTAR (NSECT), it will not affect the accuracy of the

calculation. The values of this variable are read in with an E11.4 format and must be right justified in columns 45-55.

The overall format for this data group is (7(E11.4)) and the data group is contained on a single data card. If NVI = 1, this data group is not read in.

The data input starting with AS(NSECT) above must be repeated for each electrical section of the precipitator, proceeding from the inlet to the outlet of the precipitator. Thus, the data group containing AS(NSECT) and possibly the data group containing RFS(NSECT) must be read in NUMSEC different times.

At this point, the basic data set has been entered into the program and precipitator performance will be projected based on the inputted data. The last card in the data section must have a 99 in columns 1-2. This causes the program to terminate normally.

CONSTRUCTION OF SHORTENED DATA SETS

Once the basic data set is processed, then all the parameters which are needed by the program to calculate precipitator performance are stored in memory. By using values of NDATA equal to 2, 3, or 4, shortened data sets can be entered after the basic data set in order to analyze the effects of particle size distribution, specific collection area, and electrical conditions on precipitator performance. In the shortened data sets, the values of a small number of variables which are stored in memory are changed to new values in order to produce a new set of data.

In each shortened data set, the first two data groups and data cards which are read in are the same as those discussed for the basic data set. The value of NDATA on the first data card determines the variables in memory that will be changed. The effects of particle size distribution on precipitator performance can be analyzed by setting NDATA = 2. In this case, the third data group which is read in depends upon the value of NDIST which is stored in memory. If NDIST = 2, an inlet mass median diameter (D50) and geometric standard deviation (SIGMAP) must be read in according to the same specifications discussed for the basic data set. If NDIST = 1, cumulative percents (PRCU(I)) corresponding to the particle sizes (ENDPT(I)) stored in memory must be read in according to the same specifications discussed for the basic data set. After the third data group is read in, the shortened data set is complete. By repeating this type of shortened data with different choices of D50 and SIGMAP or PRCU(I), the effects of particle size distribution can be analyzed with the use of only a few data cards.

The effects of specific collection area (SCA) on precipitator performance can be analyzed by setting NDATA = 3. In this case, the following is a sequential listing of the variables which are inputted in the third data group, along with the descriptions of the variables and the format specifications.

(1) VGS(I) is the total gas volume flow rate in a given electrical section and is in units of actual ft^3/min. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11, 23-33, and 45-55.

(2) VGASS(I) is the gas velocity in a given electrical section and is in units of ft/sec. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22, 34-44, and 56-66.

There must be a value of VGS(I) and VGASS(I) entered for each electrical section. The overall format for this data group is (3(2E11.4)) and the data group is contained on 4 or less cards depending on the value of NUMSEC which is stored in memory. For NUMSEC $\le$ 3, 3<NUMSEC $\le$ 6, 6<NUMSEC $\le$ 9, and NUMSEC = 10, the number of data cards necessary are 1, 2, 3, and 4, respectively.

After this data group is read in, the shortened data set is complete. By repeating this type of shortened data set with different choices of VGS(I) and VGASS(I), the effects of specific collection area can be analyzed with the use of only a few data cards.

The effects of applied voltage and current on precipitator performance can be analyzed by setting NDATA = 4. In this case, the following is a sequential listing of the variables which are inputted in the third data group, along with the descriptions of the variables and the format specifications.

(1) VOS(I) is the applied voltage in a given electrical section and is in units of volts. If the value of NVI stored in memory is 1, the value of VOS(I) corresponds to a measured or known value. If the value of NVI stored in memory is 2, VOS(I) corresponds to an applied voltage up to which a voltage-current curve will be calculated. Then, this applied voltage along with the corresponding current will be used in the calculation of precipitator performance. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11, 23-33, and 45-55.

(2) TCS(I) is the total current in a given electrical section and is in units of amperes. If the value of NVI stored in memory is 1, TCS(I) corresponds to a measured or known value. If the value of NVI stored in memory is 2, TCS(I) has no meaning in

terms of input data since it will be calculated in the program. In this case, the appropriate columns on the data cards can be left blank or any arbitrary number can be entered. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22, 34-44, and 56-66.

There must be a value of VOS(I) and TCS(I) entered for each electrical section. The overall format for this data group is (3(2E11.4)) and the data group is contained on 4 or less cards depending on the value of NUMSEC which is stored in memory. For NUMSEC ≤ 3, 3<NUMSEC ≤ 6, 6<NUMSEC ≤ 9, and NUMSEC = 10, the number of data cards necessary are 1, 2, 3, and 4, respectively.

After this data group is read in, the shortened data set is complete. By repeating this type of shortened data set with different choices of VOS(I) and TCS(I), the effects of voltage and current can be analyzed with the use of only a few data cards.

DYNAMIC RAPPING DATA SET

If NRAP ≠ 0 on the first data card, then additional data will need to be read into the program for the dynamic rapping process. This data, which is defined below, follows the basic data set. The maximum number of incremental lengths is limited to 45 when dynamic rapping is used.

(1) TIMRAP is the time at which a rap occurs. This variable is read in with an F10.5 format in columns 1-10. and is in units of minutes.

(2) MAPRAP(I) is an indicator which specifies which increments of the precipitator are included in the rap. (These increments are the same calculation increments defined by the variable LSECT in the basic data set.) Since the maximum number of increments is 45, MAPRAP is read in with a 45I1 format. If TIMRAP > 0 and MAPRAP(I) > 0, then the Ith increment of the precipitator is defined as having been rapped. The program sets the dust thickness on the collection plate at increment I equal to 0 and stores a portion of the collected dust for reintroduction into the gas flow at that point. If TIMRAP > 0 and MAPRAP(I) = 0, then the Ith increment was not rapped. If TIMRAP = 0 and MAPRAP(1) ≠ 0, the program will treat the next card as the beginning of an all new rapping scheme. In this case, the next card read in will be the first TIMRAP card of the new scheme. If TIMRAP = 0 and MAPRAP(1) = 0, the rapping calculation is terminated and the program resumes normal operation. The next card that will be read in this case is card 1 of the basic data set. MAPRAP is located in columns 11-55.

(3) **REPCT** is the fraction of the dust collected in one electrical section that is reentrained during the time required for the gas to flow past one computational length increment, LINCS. This is defined by

$$\text{REPCT} = \frac{\text{F}}{\text{NLANES}} * \frac{\text{Duration of gas flow past one increment}}{\text{Total duration of each rapping puff}}, \qquad (112)$$

where F is the total fraction of the collected dust that will be reentrained during a rap and NLANES is the number of parallel lanes in the section which are rapped at different times.

(4) **NUMBOL** is the number of data points in the reentrainment profile. NUMBOL is read in with an I2 format and must be right justified in columns 61-65.

(5) **NDAT** is an indicator which can assume the values of 0 or 1. If NDAT = 1, the subsequent cards will define the rapping profile. If NDAT = 0, the existing rapping profile will be used in this rap. NDAT is read in with an I5 format and must be right justified in columns 66-70.

The overall format for this card is (F10.5, 45I1, F5.3, 2I5). This card is used to define each rap of the precipitator. If two or more sections of the precipitator are rapped at the same time, a single card can contain all of the necessary information. However, any rap which occurs at a different time will require another TIMRAP card.

If NDAT = 1 on the TIMRAP card, the following cards must be inserted following that card to define the rapping profile:

(1) **BOLFRC(I,J)** are the data points used to construct the normalized histogram of fractions of dust reentrained in a given time interval. There must be NUMBOL values of BOLFRC on the card. BOLFRC is read into the program with an F6.3 format.

The overal format of this card is (13F6.3). The program expects the number of BOLFRC cards to equal the number of precipitator sections (NUMSEC) so that a different reentrainment histogram may be read in for each section. After NUMSEC cards are read, the following data is expected:

(1) REMMD(I,J) are the mass median diameters for a log-normal size distribution associated with each step of the histrogram defined by BOLFRC(I,J). There must be NUMBOL values of REMMD on the card. REMMD is read with an F6.3 format and must be in units of μm.

(2) RESIG(J) is the geometric standard deviation of the log-normal size distributions defined by REMMD. The value of RESIG must be equal to or greater than 1. RESIG is read in an F6.3 format immediately following the last value of REMMD(I,J).

The overall format of this card is (13F6.3). The program expects to read NUMSEC REMMD cards to match the NUMSEC BOLFRC cards. After these cards are used, the following card is read in:

(1) BOLTIM(I) are the durations in seconds of each of the steps of the rapping histogram. The sum of the values of BOLTIM(I) is the total duration of the rapping emissions and must obey the following relation:

$$\Sigma \text{ Boltim(I)} = \text{NLANES*Total duration of each rapping puff} \tag{113}$$

The total duration of the rapping emissions must not exceed the time between raps as the model cannot correct for overlapping rapping puffs. There must be NUMBOL values of BOLTIM on the card in an F6.3 format.

(2) DDRAP is the particle density of the reentrained dust. DD rap is in units of kg/m^3 and is read in with an F6.3 format.

The overall format of this card is (13F6.3). Only 1 BOLTIM card will be read in as the durations of the steps in the histogram are assumed to be the same for all sections of the precipitator. The rapping profile must be read in after the first TIMRAP card. Thereafter, it may be read in if it is changed. After the BOLTIM card is read in, the next card expected by the program is a new TIMRAP card.

OPACITY DATA SET

In the calculation of precipitator outlet opacity, additional data is required if NCOMPS is greater than 0. If NCOMPS > 0 and NLAMDA = 0, user supplied values of the read and imaginary parts of the index of refraction must be read into the program:

(1) CMR(I) is the real part of the user supplied index of refraction. This quantity is read in with an F5.3 format.

(2) CMI(I) is the imaginery part of the user supplied index of refraction. CMI(I) is read with an F5.3 format.

The NCOMPS values of CMR(I) and CMI(I) are read in as data pairs with an overall format of (6(2F5.3)).

If NCOMPS > 0 and NLAMDA > 0, then the index of refraction changes with wavelength. In this case the following data are read in:

(1) CMR(J) is the real part of the user supplied index of refraction for wavelengths ranging from the value of UPTOLM(J-1) (assumed to be 0.43 μm if J = 1) to the value of UPTOLM(J). CMR is read in with an F5.3 format.

(2) CMI(J) is the imaginary part of the user supplied index of refraction for wavelengths ranging from the value of UPTOLM(J-1) to the value of UPTOLM(J). CMI is read in with an F5.3 format.

(3) UPTOLM(J) is the upper limit of the wavelength band for which CMR(J) and CMI(J) are the correct indices of refraction. UPTOLM is in units of μm and is read in with an F5.3 format. The final value of UPTOLM(J) must be equal to or greater than 0.70.

The NLAMDA values of CMR(J), CMI(J), and UPTOLM(J) are read in the form of data groups, each complete for a given value of J. The overall format for this data is (4(3F5.2)).

UNKNOWN OPERATING CONDITIONS

The model may be used to calculate V-I curves and collection efficiencies for precipitators with unknown operating voltages and currents. Table 6 summarizes the options available to the user and makes recommendations on the applicability of each. If collection efficiency data for a utililty fly ash precipitator is desired, the following data set should be used.

The first data card has the same format as the first card in the basic data set. MODL must be set to 2 in column 8. Since the remainder of the data in this data group is redefined in subroutine INTERN, the rest of the card may be left blank if desired.

Table 6. User options when the operating voltage and current are not known

Desired Calculation	Variables MODL	 NVI	 VISKIP	 VISAME	Procedure Recommended	Comments
Collection efficiency of a utility fly ash precipitator.	2	1	n/a	n/a	Yes	Uses internal data set based on 17 field tests of cold-side utility fly ash precipitators to generate efficiencies for a range of SCA values. Fast.
	0 or 1	2	1	1 or 2	No	Calculates approximate V-I curves; then calcules efficiency for a derived operating point. Slow. VISAME=2 (different voltages in each section) is slower than VISAME=1 (same voltage).
Collection efficiency for an ESP that is much different from a utility fly ash ESP.	2	1	n/a	n/a	No	Precipitator test data used in internal data set are not similar to this application. Accuracy may be low. Fast.
	0 or 1	2	1	1	Yes	Calculates approximate V-I curves; then calculates efficiency for a derived operating point. Uses the same operating point in each ESP section. Slow.
	0 or 1	2	1	2	No	Same as above except calculates a new operating point for each ESP section. Slower.
	0 or 1	2	0	2	No	Same as above except calculates electric fields and potentials in each ESP length increment. Very slow.

Table 6. (Continued)

Desired Calculation	Variables				Procedure Recommended	Comments
	MODL	NVI	VISKIP	VISAME		
V-I curves only for a utility fly ash precipitator.	3	1	n/a	n/a	Yes	Uses internal data set to generate V-I curves. No efficiency calculated. Fast.
	3	2	1	1 or 2	No	Calculates V-I curve for first section only using approximate procedures. No efficiency calculated. Slow
V-I curves only for an ESP that is much different from a utility fly ash ESP.	3	1	n/a	n/a	No	Uses internal data set to generate V-I curves. Precipitator test data used in internal data set are not similar to this application. Accuracy may be low. Fast.
	3	2	1	1 or 2	Yes	Calculates V-I curve for first section only using approximate procedures. No efficiency calculated. Slower.

Data group 2 contains the following 2 data.

(1) RHO	is the resistivity of the collected particulate layer expressed in ohm-cm. RHO is entered with an E8.2 format and must be right justified in columns 1-8.
(2) HDUCT	is the wire-to-plate spacing in units of inches. HDUCT is read with an F5.2 format in columns 11-15.

If the ESP being studied is similar to a utility fly ash precipitator, the above procedure may be used. However, if the ESP is much different from a utility fly ash precipitator, a different procedure should be used. This procedure is enabled when NVI is set to 2 in data group 3. The description of the data required for this case is contained in the discussion of the basic data set.

If only V-I curves are desired, the required data set again depends on whether the ESP is similar to a utility fly ash precipitator. If the ESP is similar, then the first 3 data groups are the same as for the basic data set described earlier in this section. To get the V-I calculation, the following values must appear:

(1) Card 1: MODL = 3 in column 8 (the rest of the card may be blank),

(2) Card 3: NVI = 1 in column 6 (the rest of the card may be blank).

Card 4 will contain the following data:

(1) RHO	is the resistivity of the collected particulate layer expressed in ohm-cm. RHO is entered with an E8.2 format and must be right justified in columns 1-8.
(2) HDUCT	is the wire-to-plate spacing in units of inches. HDUCT is read with an F5.2 format in columns 11-15.

V-I curves and operating points for a six section ESP will be printed. If the ESP is not similar to a utility fly ash precipitator, a complete data set appropriate for an efficiency calculation with NVI set to 2 is required. If MODL = 3 on card 1, the calculation will terminate after the calculation and printing of the V-I curve data for the first electrical section.

SECTION 9

GUIDE TO THE USE OF OPTIONS

There are several options available in the operation of the ESP model. These options concern the type of data to be read into the program, the processes used to calculate the collection efficiency, which effects the calculation accuracy and the run time, and the amount of data which will be printed. The options are listed below with a discussion of the results of the different choices available. Table 7 summarizes these choices.

1. NEST determines the method by which the electric fields in the ESP are calculated. If NEST = 1, a rigorous calculation of the fields is performed by subroutines EFLD1 or EFLD2 (determined by NVI). If NEST = 2, the fields are estimated, resulting in a time reduction of about a factor of 15. However, the accuracy of the estimated fields varies with the application and in some cases, the estimated efficiencies may differ appreciably from the rigorously calculated values. If NEST = 2, the particle charges are calculated as if NCALC = 1. Table 8 shows some of the effects of changing this variable.

2. NVI determines whether the electric field calculation will be performed by subroutine EFLD1 or subroutine EFLD2. If the operating conditions are known, setting NVI = 1 will cause EFLD1 to calculate the fields. If the operating conditions are not known, setting NVI = 2 will cause EFLD2 to calculate a V-I curve to determine the operating conditions and then calculate the electric fields. This process takes much more computer time than the field calculation from known operating conditions.

3. NCALC determines the method of calculating the particle charge. If NCALC = 0, equation 12 is integrated to give the charge. If NCALC = 1, the charge is found from equation 15, which gives the sum of the charges from classical field and diffusion charging theories. In general, equation 15 gives fairly accurate results in much less time; however, for careful work, equation 12 should be used. Table 8 shows some of the effects of changing this variable.

4. NDIST determines the type of inlet particle size distribution data which must be read into the program. If NDIST = 1, the user must supply a measured particle size distribution. If

TABLE 7
SUMMARY OF PROGRAMMING OPTIONS

Variable	Value	Effected Process	Effect	Subroutines	Accuracy	Time	Comments
NEST	1	Calculation of electric fields	Rigorous calculation	EFLD1,EFLD2	High	High	
	2		Estimation	-	Variable	Low	Estimates particle charge
NVI	1	Calculation of electric fields	Input known operating conditions	EFLD1	Higher	Lower	
	2		Calculate operating conditions	EFLD2	Lower	Higher	Time is much higher
NCALC	0	Calculation of particle charge	Integrated charge (eq. 12)	CHARGN	High	High	
	1		Summed charge (eq. 15)	CHARGSUM	Variable	Low	
NDIST	1	Inlet particle size distribution	User supplied distribution	LNFIT	Higher	Same	Use NDIST=1 if possible as distribution may not be log-normal
	2		Calculated log-normal distribution	LNDIST	Lower	Same	
NRAP	0	Calculation of rapping re-entrainment	Estimation	ADJUST	Good	Low	Average of 6 power plants
	1-3		Dynamic calculation	RAPPE	Variable	High	Must be tailored to each use. Very flexible. Use NEST=2 due length.
MODL	0	Type of input data	Same input data as Revision 1	-	-	-	-
	1		All metric input data	-	-	-	-
	2		Internal data set	INTERN	-	-	Requires resistivity and wire-to-plate spacing only
	3		Stops after V-I curve printed	EFLD2 or INTERN	-	-	-
NOPRNT	0	Amount of output data printed	All data printed	-	-	-	-
	1		Particle charging data and some opacity data not printed	-	-	-	-
	2		Also deletes printing of incremental data	-	-	-	-
NNPRINT	-	Data checking routine output	Allows data diagnostics to be separated from other output	CHEKIN	-	-	-

TABLE 8. EFFECTS OF VARYING NEST AND NCALC

	NEST	NCALC	TIME(SEC)	EFFICIENCY(%)
ESP #1	1	0	152	95.99
	1	1	89	96.69
	2	1	8	96.93
ESP #2*	1	0	2068	86.0
	1	1	775	83.2
ESP #3	1	0	1684	99.31**
	1	1	600	99.66
	2	1	97	99.71

*For NVI = 2, setting NEST = 2 has the same effect as setting NCALC = 1.

**Only the first of the 4 efficiencies calculated is shown.

NDIST = 2, the program calculates a log-normal distribution based on parameters provided by the user. Since some inlet size distributions differ significantly from a log-normal distribution, it is important to use measured data if it is available.

5. NRAP determines which type of rapping reentrainment calculation will be performed and how much data will be printed. If NRAP = 0, the collection efficiency will be adjusted by an empirical relationship based on a rapping reentrainment study in 6 coal-fired power plants. This adjustment takes very little time and yields good results for full-sized precipitators collecting fly ash. There is inadequate data to evaluate the suitability of this correction for precipitators collecting other materials. If NRAP = 1, 2, or 3, the rapping reentrainment calculation is performed by repeating the collection efficiency calculation with the reentrained dust being added to the dust already present in the gas flow at the point of reentrainment. The advantage of this process is that it is highly flexible and can be used to study changes in the rapping pattern. The disadvantages are that there is no standard data set available (instead the data must be tailored to each application) and that a large increase in computer time is required. The time increase is at least 2n where n is the number of raps in the rapping schedule. If only the rap of the last section is modeled, this is still a factor of 2. For this reason, the use of the estimation procedures (NEST = 2) is recommended when NRAP ≠ 0.

6. MODL determines the type of input data required by the program. If MODL = 0, the data set must be in the mixed metric-English units required by previous versions of the model. If MODL = 1, the data must be entirely in metric units. If MODL = 2, only resistivity and wire-to-plate spacing are read into the program. The remainder of the data is contained in subroutine INTERN. This option causes the model to generate efficiency data based on a study of utility fly ash precipitators for a wide range of SCA values. This is useful as a first step in establishing the ESP requirements for a particular application. However, it must be emphasized that this procedure can only provide a rough estimate of ESP needs for use as a starting point in a rigorous investigation. If MODL = 3, the program serves as a V-I curve generator.

7. NOPRNT determines the amount of charging and opacity data which is printed. If NOPRNT ≠ 0, the particle charge summary is not printed. The printing of differential opacity data is also deleted, leaving only the total opacity figures. The purpose of this option is to reduce the number of pages of printed output when the deleted data is not needed.

8. Subroutine CHEKIN checks the input data for errors or unusually large or small values of the ESP operating conditions. Warning messages generated in this subroutine are listed at the top of the printed output of the program. In some cases it may be desirable to print these messages to a different file or device than the remainder of the program output. This can be accomplished by changing one statement in subroutine CHECKIN. In the main routine, the variable NPRNT is used to define the distination device for the program output. In subroutine CHEKIN, the output distination is defined by the variable NNPRNT which is set equal to NPRNT. To change the distination of the warning messages, NNPRNT must be redefined. A comment statement identifies the proper statement in subroutine CHEKIN.

SECTION 10

MACHINE-DEPENDENT FACTORS OF THE COMPUTER PROGRAM

Revision 3 of the ESP model is written in the FORTRAN IV language. Although this program was developed on a Digital Equipment Corporation DEC 2020 computer, it can be run on other computer systems with very few changes. For most computers, the first two executable statements in the program are the only changes required. The first of these defines the input (read) device unit number with the variable name NREAD. The second statement defines the output (write) device unit numbers with the variable name NPRNT. In order to run the program on a Control Data Corporation (CDC) computer system, it may also be necessary to change the single quotes found in many of the format statements to double quotes.

The FORTRAN code for the ESP model occupies 205,799 bytes of memory (7 bit) on the DEC System 20 computer. This is well within the memory limits of modern main-frame computers as well as many mini-computers. If the available computer does not have adequate memory, there are several ways in which the program size may be reduced. The first method is to eliminate those functions and options which will not be used. Several of the less essential functions have been identified and the fortran statements used only with those functions have been tagged in columns 72-80. These functions and their identifying tags are listed in Table 9. If the tag occurs on the first line of a subroutine, the entire subroutine is to be considered tagged. If all of the tagged statements and subroutines are removed from the program, the program length is reduced to 135,014 bytes. Two other methods of reducing the program length are by overlaying the program and by changing the sizes of the arrays within the program. Overlaying the program will allow all of the program functions to be retained but the computer will see only part of the program at any one time. The overlaying scheme must be custom designed for each application. The third size-reduction method, changing the sizes of the arrays, should only be considered in extreme cases as a very detailed study of the model is required to change the many interrelated variables involved.

A major factor in the use of a computer program of this size is the cost of operation. The greatest factor in the cost is usually the time the computer spends in performing the calculations

TABLE 9. FUNCTIONS TAGGED FOR EASY REMOVAL

Function	Tag
Dynamic rapping	RAP
Opacity calculation	OPAC
Internal data set	INT
Input data check	CHEK
Calculation of unknown electrical conditions	E2

(often referred to as central processing unit (CPU) time). Revision 3 of the model uses about one-tenth of the CPU time required by Revision 1 and should therefore be much less expensive to operate. In some cases, users are also charged according to the size of the program, although this practice is becoming much less common with large time-sharing machines. If such charges are imposed, the users should consider shortening the program as outlined in the previous paragraph. Frequent users of the model may reduce costs by using a compiled (i.e., machine language) version of the program rather than a FORTRAN version.

REFERENCES

1. Gooch, J. P., J. R. McDonald, and S. Oglesby, Jr. A Mathematical Model of Electrostatic Precipitation. EPA-650/2-75-037, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1975.

2. McDonald, J. R. A Mathematical Model of Electrostatic Precipitation (Revision 1): Volume I. Modeling and Programming. EPA-600/7-78-111a (NTIS PB284-614), U.S. EPA, IERL, Research Triangle Park, North Carolina, June 1978.

3. McDonald, J. R. A Mathematical Model of Electrostatic Precipitation (Revision 1): Volume II. User Manual. EPA-100/7-78-111b (NTIS PB284-615), U.S. EPA, IERL, Research Triangle Park, North Carolina, June 1978.

4. Mosley, R. B., M. H. Anderson, and J. R. McDonald. A Mathematical Model of Electrostatic Precipitation (Revision 2). EPA-600/7-80-034, U.S. EPA, IERL, Research Triangle Park, North Carolina, February 1980.

5. Felder, R. M., and E. Arce-Medina. Improvements in an Algorithm for Calculating the Potential Field Distribution and Current Density in a Parallel Plate Electrostatic Precipitator. Grant No. R805404010, U.S. EPA, IERL, Research Triangle Park, North Carolina, May 1980.

6. McDonald, J. R., M. H. Anderson, R. B. Mosley, and L. E. Sparks. Charge Measurements on Individual Particles Exiting Laboratory Precipitators. Presented at the EPA Symposium on the Transfer and Utilization of Particulate Control Technology, Denver, Colorado, Paper A7-1, July 23-26, 1979.

7. Pauthenier, M., and M. Moreau-Hanot. Charging of Spherical Particles in an Ionizing Field. J. Phys. Radium, 3(7):590-613, 1932.

8. White, H. J. Particle Charging in Electrostatic Precipitation. Trans. Amer. Inst. Elec. Eng. Part 1, 70:1186-1191, 1951.

9. Murphy, A. T., F. T. Adler, and G. W. Penney. A Theoretical Analysis of the Effects of an Electric Field on the Charging of Fine Particles. Trans. Amer. Inst. Elec. Eng., 78:318-326, 1959.

10. White, H. J. Industrial Electrostatic Precipitation. Addison-Wesley, Reading, Massachusetts, 1963. p. 157.

11. Fuchs, N. A. The Mechanics of Aerosols. Chapter 2. Macmillan, New York, 1964.

12. White, H. J. Reference 8, pp. 166-170.

13. White, H. J. Reference 8, pp. 185-190.

14. Penney, G. W., and S. Craig. Pulsed Discharges Preceding Sparkover at Low Voltage Gradients. AIEE Winter General Meeting, New York, 1961.

15. Pottinger, J. F. The Collection of Difficult Materials by Electrostatic Precipitation. Australian Chem. Process Eng., 20(2):17-23, 1967.

16. Spencer, H. W. Electrostatic Precipitators: Relationship Between Resistivity, Particle Size, and Sparkover. EPA-600/2-76-144, U.S. Environmental Protection Agency, Raleigh Durham, North Carolina, 1976.

17. Bickelhaupt, R. E. Surface Resistivity and the Chemical Composition of Fly Ash. APCA Journal, 25(2):148-152, 1975.

18. Bickelhaupt, R. E. Volume Resistivity - Fly Ash Composition Relationship. Environmental Sc. & Tech., 9(4):336-342, 1975.

19. Selle, S. J., L. L. Hess, and E. A. Sondreal. Western Fly Ash Composition as an Indicator of Resistivity and Pilot ESP Removal Efficiency. Paper 75-02.5 presented at the 68th Meeting of the Air Pollution Control Association, Boston, Massachusetts, 1975.

20. Bickelhaupt, R. E. A Technique for Predicting Fly Ash Resistivity. EPA-600/7-79-204, U.S. EPA, IERL, Research Triangle Park, North Carolina, August 1979.

21. White, H. J. Reference 8, pp. 238-293.

22. Preszler, L., and T. Lajos. Uniformity of the Velocity Distribution Upon Entry into an Electrostatic Precipitator of a Flowing Gas. Staub Reinhalt. Luft (in English), 32(11):1-7, 1972.

23. Gooch, J. P., and G. H. Marchant, Jr. Electrostatic Precipitator Rapping Reentrainment and Computer Model Studies. EPRI Contract RP413-1, The Electric Power Research Institute, Palo Alto, CA, June 1978.

24. Spencer, H. W. A Study of Rapping Reentrainment in a Nearly Full Scale Pilot Electrostatic Precipitator. EPA-600/2-76-140, U.S. Environmental Protection Agency, Raleigh Durham, North Carolina, 1976.

25. Leutert, G., and B. Böhlen. The Spatial Trend of Electric Field Strength and Space Charge Density in Plate-Type Electrostatic Precipitators. Staub, 32(7):27, 1972.

26. McDonald, J. R., W. B. Smith, H. W. Spencer, and L. E. Sparks. A Mathematical Model for Calculating Electrical Conditions in Wire-Duct Electrostatic Precipitation Devices. J. Appl. Phys., 48(6):2231-2246, 1977.

27. Smith, W. B., and J. R. McDonald. Development of a Theory for the Charging of Particles by Unipolar Ions. J. Aerosol Sci., 7:151-166, 1976.

28. Hewitt, G. W. The Charging of Small Particles for Electrostatic Precipitation. AIEE Trans., 76:300, 1957.

29. Oglesby, S., and G. B. Nichols. A Manual of Electrostatic Precipitator Technology: Part I, Fundamentals. NTIS PB 196380, APTD 0610, National Air Pollution Control Administration, Cincinnati, Ohio, 1970. pp. 57-66.

30. McDonald, J. R. Mathematical Modelling of Electrical Conditions, Particle Charging, and the Electrostatic Precipitation Process. Ph.D. Dissertation, Physics Dept., Auburn University, Auburn, Alabama, 1977. pp. 47-54.

31. Mie, G. Beitrage zur Optik truber Medien, Speziell Kolloidaler Metallosunge. Ann. Physik. 25:377-445, 1908.

32. Cooperman, P. The Dependence of the Electrical Characteristics of Duct Precipitators on Their Geometry. Unpublished Report, Research Corp., 1952.

33. Nielsen, K. L. Methods in Numerical Analysis, 3rd Edition. The MacMillan Company, New York, 1964. pp. 236-239.

34. Conte, S. D. Elementary Numerical Analysis. McGraw-Hill Book Company, New York, New York, 1965. p. 138.

35. CRC Standard Mathematical Tables. Fourteenth Edition, edited by Samuel M. Selby, The Chemical Rubber Co., Cleveland, Ohio, 1965. p. 409.

36. Murphy, A. T. Charging of Particles by Random Motion of Ions in an Electric Field. Ph.D. Dissertation, Dept. of Electrical Engineering, Carnegie Institute of Technology, Pittsburgh, Pa., 1957. p. 59.

37. Hildebrand, F. B. Introduction to Numerical Analysis. McGraw-Hill, Inc., New York, 1956. p. 75.

38. Hastings, C., Jr. Approximations for Digital Computers. Princeton University Press, Princeton, New Jersey, 1955. p. 192.

39. Bevington, P. R. Data Reduction and Error Analysis for the Physical Sciences. McGraw-Hill, Inc., New York, 1969. pp. 99-122.

40. Pilat, M. J., and D. S. Ensor. Plume Opacity and Particulate Mass Concentration. Atmos. Environ. 4:163-167, 1970.

41. van de Hulst, H. C., Light Scattering by Small Particles. John Wiley and Sons, New York: 1957.

42. Moore, J. D. M. Tests of Approximations to Electromagnetic Scattering by Spherical Particles. M.S. Thesis. Auburn University, Auburn, Alabama, 1968.

43. Deirmendjian, D., and R. J. Clason. Light Scattering on Partially Absorbing Homogeneous Spheres of Finite Size. Paper R393-PR, The RAND Corporation, Santa Monica, California, 1962.

44. DuBard, J. L., and R. F. Altman. Prediction of Electrical Operating Points for use in a Precipitator Sizing Procedure. Presented at the EPRI Conference on Electrostatic Precipitator Technology for Coal-Fired Power Plants, Nashville, Tennessee, July 14-16, 1982.

45. Spencer, H. W. Experimental Determination of the Effective Ion Mobility of Simulated Flue Gas. In: Proceedings of 1975 IEEE-IAS Conference, Atlanta, Georgia, 1975.

46. White, H. J. Reference 8, p. 92.

APPENDIX A

A PROCEDURE FOR DETERMINING SPACE CHARGE EFFECTS

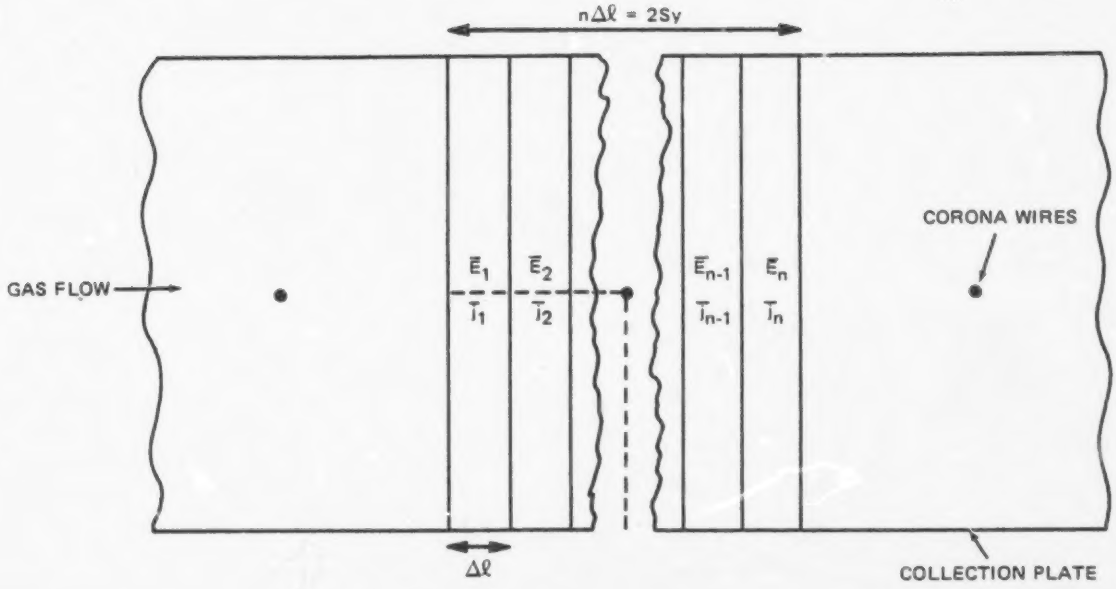
When particles are introduced into a precipitator, the mechanisms of particle charging and particle collection come into play. In order to account for the dynamics of these mechanisms, it is necessary to determine the ion density and electric field distributions to which the particles will be subjected. These are obtained for the flue gas without particles by calculating a voltage-current curve using the technique discussed earlier. The reliability of this calculation will depend to a large extent on the choice of ion "effective mobility", used to represent clean flue gas, and the condition of the discharge electrodes. Representative values of ion "effective mobility" should be obtained from in situ measurements, or laboratory measurements made on gases of similar composition in the proper environment.[45] The condition of the discharge wires with regards to roughness is accounted for by a roughness factor f.[46] This factor normally lies in the range of 0.5-1.0 and has a significant effect on the space charge density near the discharge electrode.

For the desired operating voltage and current which are obtained from the "clean" voltage-current curve, the corresponding current density and electric field distributions are used to determine average current densities $\bar{j}_\ell$ and average electric fields $\bar{E}_\ell$ for n incremental lengths $\Delta\ell$ contained in wire-to-wire spacings centered on the wires. This formulation is depicted in Figure 35. The incremental lengths $\Delta\ell$ are the same size as the grid spacings in the direction of gas flow used in the calculation of the electrical conditions. Using symmetry considerations, we can obtain all the information shown in Figure 35 from calculations based on the area enclosed in the dashed lines. Although this formulism does not provide a complete positional description, it does allow for the effects of nonuniform current density and electric field on particle charging and particle collection.

The values of the $\bar{j}_\ell$ and $\bar{E}_\ell$ and the designated particle charging equation are used to calculate the charge $q_{i,\ell}$ on each particle size i at the end of the ℓ-th incremental length. In the regions midway between wires, the particle charging rate will be lowest due to lower values of $\bar{j}_\ell$ and $\bar{E}_\ell$. As uncollected particles move toward regions directly between a wire and the plate, the charging rate will tend to increase due to higher values of $\bar{j}_\ell$ and $\bar{E}_\ell$.

The average charge density $\bar{\rho}_\ell$ due to the total particulate loading in the ℓ-th incremental length is given by

$$\bar{\rho}_\ell = \sum_i \bar{\rho}_{i,\ell} = \sum_i x_{i,\ell}\, q_{i,\ell} \quad , \qquad (114)$$


$n\Delta\ell = 2S_y$
GAS FLOW
$\bar{E}_1$
$\bar{E}_2$
$\bar{E}_{n-1}$
$\bar{E}_n$
$\bar{j}_1$
$\bar{j}_2$
$\bar{j}_{n-1}$
$\bar{j}_n$
CORONA WIRES
$\Delta\ell$
COLLECTION PLATE

n = NUMBER OF INCREMENTAL LENGTHS CONTAINED IN ONE WIRE-TO-WIRE SPACING

S_y = ONE-HALF THE WIRE-TO-WIRE SPACING

$\Delta\ell$ = INCREMENTAL LENGTH

$\bar{E}_\ell$ = AVERAGE ELECTRIC FIELD IN ℓ-TH INCREMENTAL LENGTH

$\bar{j}_\ell$ = AVERAGE CURRENT DENSITY IN ℓ-TH INCREMENTAL LENGTH

Figure 35. *Nomenclature used in the procedure which determines particulate space charge effects.*

where $\bar{\rho}_{i,\ell}$ = average charge density for the i-th particle size at the end of the ℓ-th incremental length (coul/m^3), and

$X_{i,\ell}$ = number of particles per unit volume of gas of the i-th particle size entering the ℓ-th incremental length (m^{-3}).

A weighted particulate mobility $\bar{b}_\ell$ due to all particles in the ℓ-th incremental length can be defined as

$$\bar{b}_\ell = \frac{\sum_i (X_{i,\ell}\, q_{i,\ell}\, C_i)/(6\pi\mu a_i)}{\sum_i X_{i,\ell}}$$

$$= \frac{\sum_i (\bar{\rho}_{i,\ell}\, C_i)/(6\pi\mu a_i)}{X_\ell} \quad , \tag{115}$$

where C_i = Cunningham correction factor for the i-th particle size,

μ = viscosity of the gas (kg/m-sec),

a_i = radius of the i-th particle size (m), and

X_ℓ = total number of particles per unit volume of gas entering the ℓ-th incremental length (m^{-3}).

The average ionic charge density $\bar{\rho}'_\ell$ with a mass loading in the ℓ-th incremental length is obtained from

$$\bar{\rho}'_\ell = \frac{\bar{J}_\ell}{b' E_\ell} - (\rho_\ell - \rho_{\ell-1})$$

$$= \bar{\rho}''_\ell - \Delta\bar{\rho}_\ell \quad , \tag{116}$$

where b' = molecular ion "effective mobility" (m^2/V-sec),

$\bar{\rho}''_\ell$ = average ionic charge density without mass loading in the ℓ-th incremental length (coul/m^3), and

$\Delta\bar{\rho}_\ell$ = average charge density shifted from molecular ions to particles in the ℓ-th incremental length (coul/m^3).

An effective mobility b^e_ℓ due to both ions and particles in the ℓ-th incremental length is found from

$$b^e_\ell = \frac{b'\bar{\rho}'_\ell + \bar{b}_\ell\,\bar{\rho}_\ell}{\bar{\rho}'_\ell + \bar{\rho}_\ell} \quad . \tag{117}$$

Since a certain number of particles will be removed from the gas stream in the ℓ-th incremental length, it is necessary to calculate collection efficiencies for the different particle sizes. The collection efficiencies are calculated using equation (5), where the migration velocities are calculated from

$$w_{i,\ell} = \frac{q_{i,\ell}\,\bar{E}^p_\ell\,C_i}{6\pi a_i \mu} \tag{118}$$

and $\bar{E}^p_\ell$ is the average electric field at the collection plate in the ℓ-th incremental length. Thus, the size distribution entering the (ℓ+1)-th incremental length is obtained from

$$X_{i,\ell+1} = (1 - \eta_{i,\ell})\,X_{i,\ell} \quad . \tag{119}$$

An "effective mobility" b^e_ℓ is calculated for each of n successive incremental lengths over a total length equal to the wire-to-wire spacing. Then, the "average effective mobility" b^e for ions and particles over a length equal to the wire-to-wire spacing is calculated from

$$b^e = \frac{1}{n}\sum_{\ell=1}^{n} b^e_\ell \tag{120}$$

The value of b^e is used to generate a voltage-current curve for the particular wire-to-wire length under consideration in order to describe the effect of particles on the electrical conditions. In this calculation, it is assumed that over several wire-to-wire spacings symmetry in the electric field and space charge density distribution is essentially preserved. Also, strictly speaking, it is not valid to generate the entire voltage-current curve with a constant value of b^e when particles are present. This is because b^e is a function of applied voltage and current density since it depends on particle charging and particle collection. However, at the operating applied voltage, the correct current density will be predicted and, in fact, the entire voltage-current curve will be approximately correct since b^e normally will not vary enough over practical voltage ranges to produce significant differences. In any case, the generation of a voltage-current curve can be viewed as a systematic procedure for searching for the current density that would exist at the operating applied voltage.

In lieu of using the time-consuming, voltage-current calculation, it is possible to estimate the operating current density for a given applied voltage from a simple relationship, provided certain considerations are made. If particles are introduced into a precipitator and the applied voltage is held fixed, then the current density at any location and the effective charge carrier mobility will be lowered. Since the product of total space charge density and electric field strength at any location is equal to the ratio of current density to effective mobility, the product tends to remain constant. If it is assumed that the limited regions of ionization near the corona electrodes are unchanged by the presence of particles, then, even though charge is transferred to particles in these regions, the space charge density and electric field near a wire will both remain essentially constant. Thus,

$$\frac{\bar{j}_w}{b'} = \frac{\bar{j}'_w}{b^e} \quad , \qquad (121)$$

where

$\bar{j}_w$ = average current density near the wire without particles (A/m^2), and

$\bar{j}'_w$ = average current density near the wire with particles (A/m^2).

The average current density at the wire is related to the average current density at the plate by

$$\bar{j}_w = (A'_p/A_w)\bar{j}_p \quad , \qquad (122)$$

where

A_p' = collection plate area receiving current from a single wire (m^2),

A_w = surface area of a single wire (m^2), and

$\bar{j}_p$ = average current density at the collection plate without particles (A/m^2).

Using equations (121) and (122),

$$\bar{j}_p' = (b^e/b')\bar{j}_p \quad , \qquad (123)$$

where $\bar{j}_p'$ (A/m^2) is the average current density at the collection plate with particles present. Equation (123) provides a simple way to estimate the reduction in current density at the plate due to the presence of particles.

The operating current densities are determined for successive wire-to-wire spacings throughout the length of the precipitator. Since the space charge scheme incorporates the dynamics of the precipitation process, particle collection efficiencies are predicted as well as operating voltages and current densities. In this scheme, no estimate of overall mass efficiency is necessary as is the case in the procedure using equation (16) and this is advantageous in designing a new precipitator.

Figures 36-42 show some theoretical trends predicted by using this space charge scheme. In these figures, the ion "effective mobility", at standard temperature and pressure, and the roughness factor were taken to be 2.2×10^{-4} $m^2/V\cdot sec$ and 1.0, respectively. The parameters used in the calculations are typical of full-scale, cold-side precipitators. The electrode geometry consists of plate-to-plate and wire-to-wire spacings of 22.86 cm and a wire radius of 0.138 cm. The inlet particle size distribution (MMD = 25 μm, $\sigma_p = 2.8$) is characteristic of fly ash obtained from the combustion of Eastern coal.

Figures 36-38 show the variation of average current density along the length of the precipitator for different inlet mass loadings, specific collection areas, and voltage levels. The different specific collection areas were obtained by leaving the plate area fixed and varying the volume flow rate. Near the inlet of the precipitator, the curves show a minimum in the average current density at the plate. This behavior might be expected since the "effective mobility" should initially decrease due to the charging process and then, as the charging process slows down

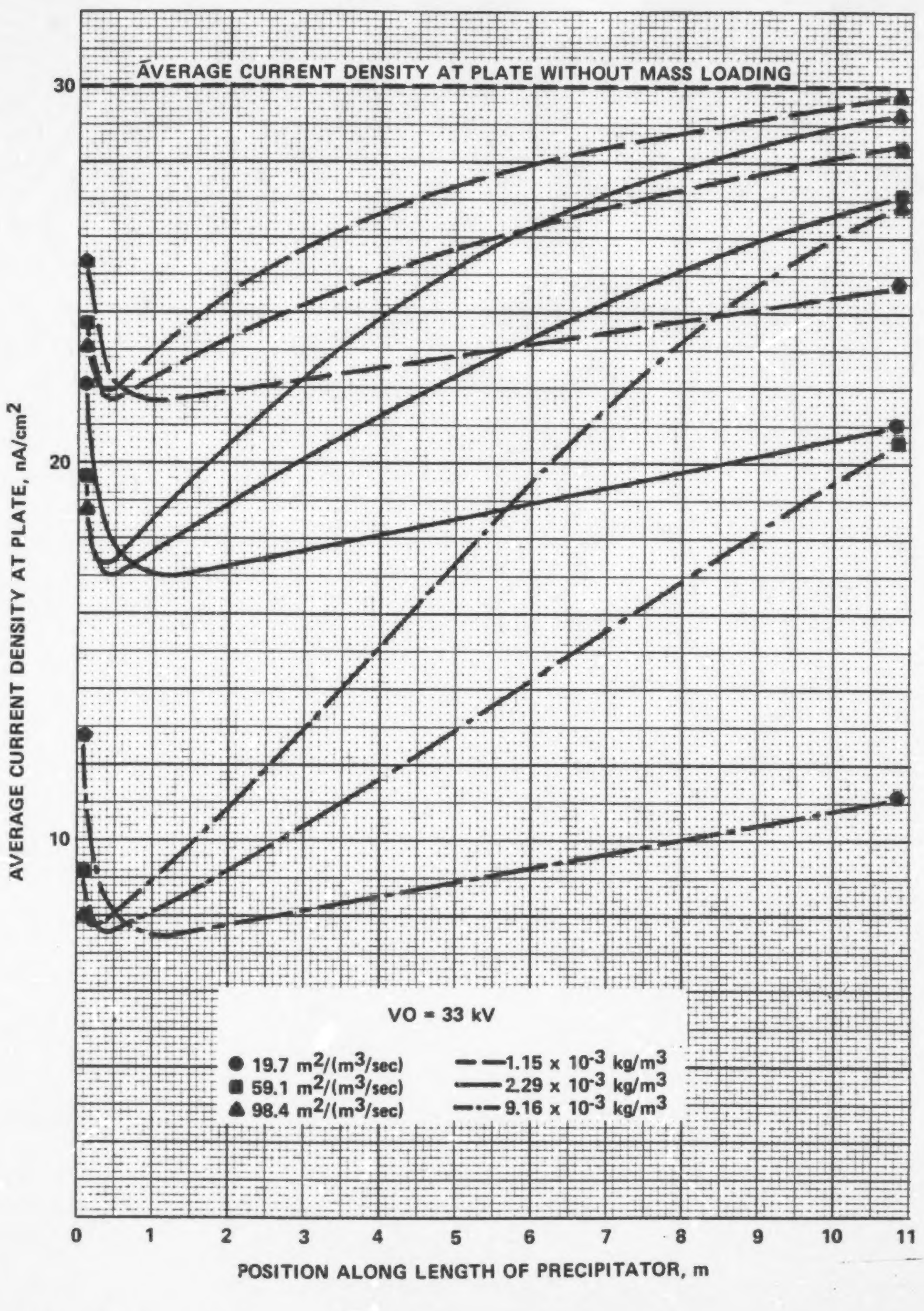


Figure 36. *Theoretical variation of average current density at the plate with precipitator length for different specific collection areas and inlet mass loadings at 33 kV.*

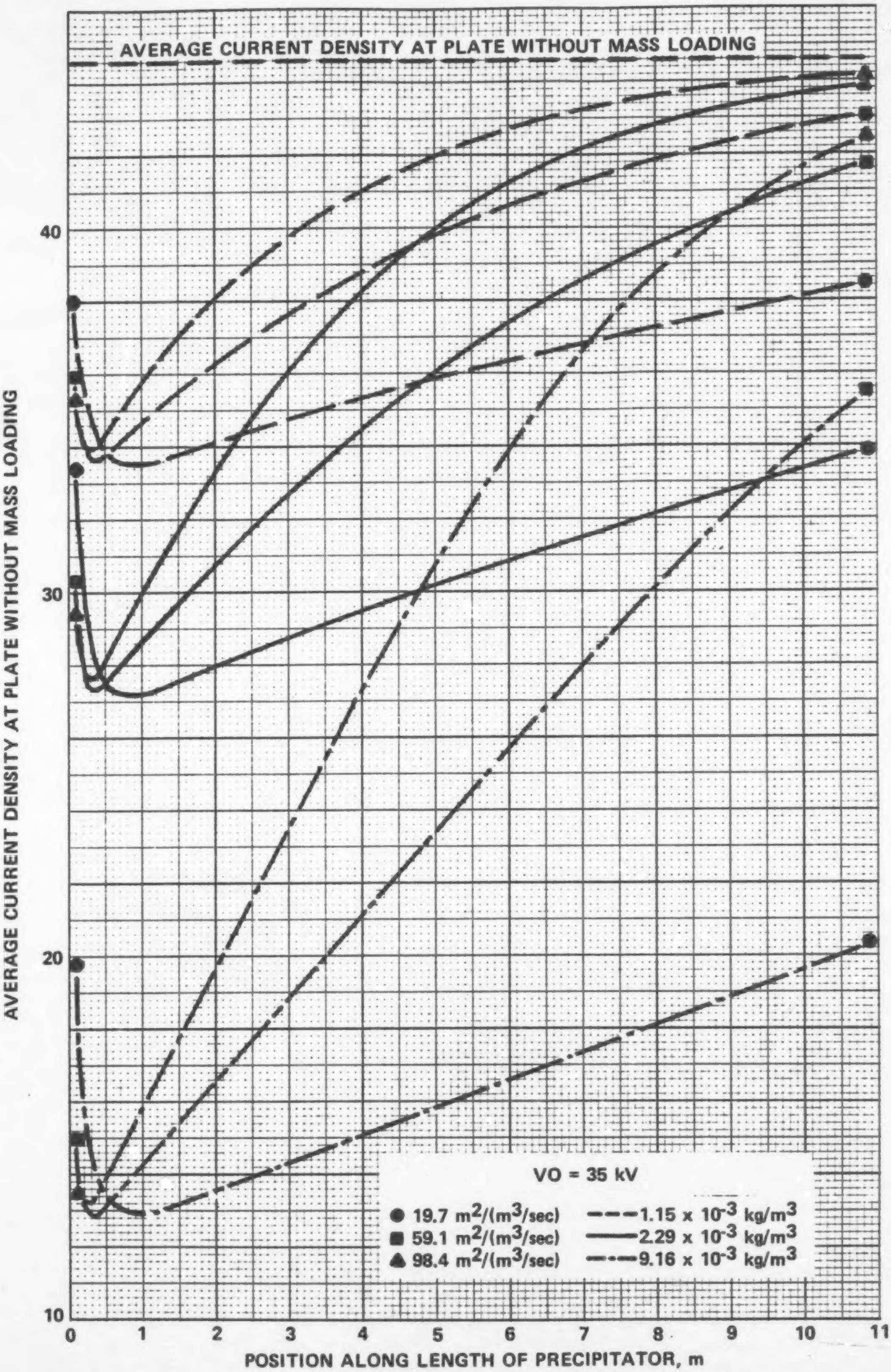


Figure 37. *Theoretical variation of average current density at the plate with precipitator length for different specific collection areas and inlet mass loadings at 35 kV.*

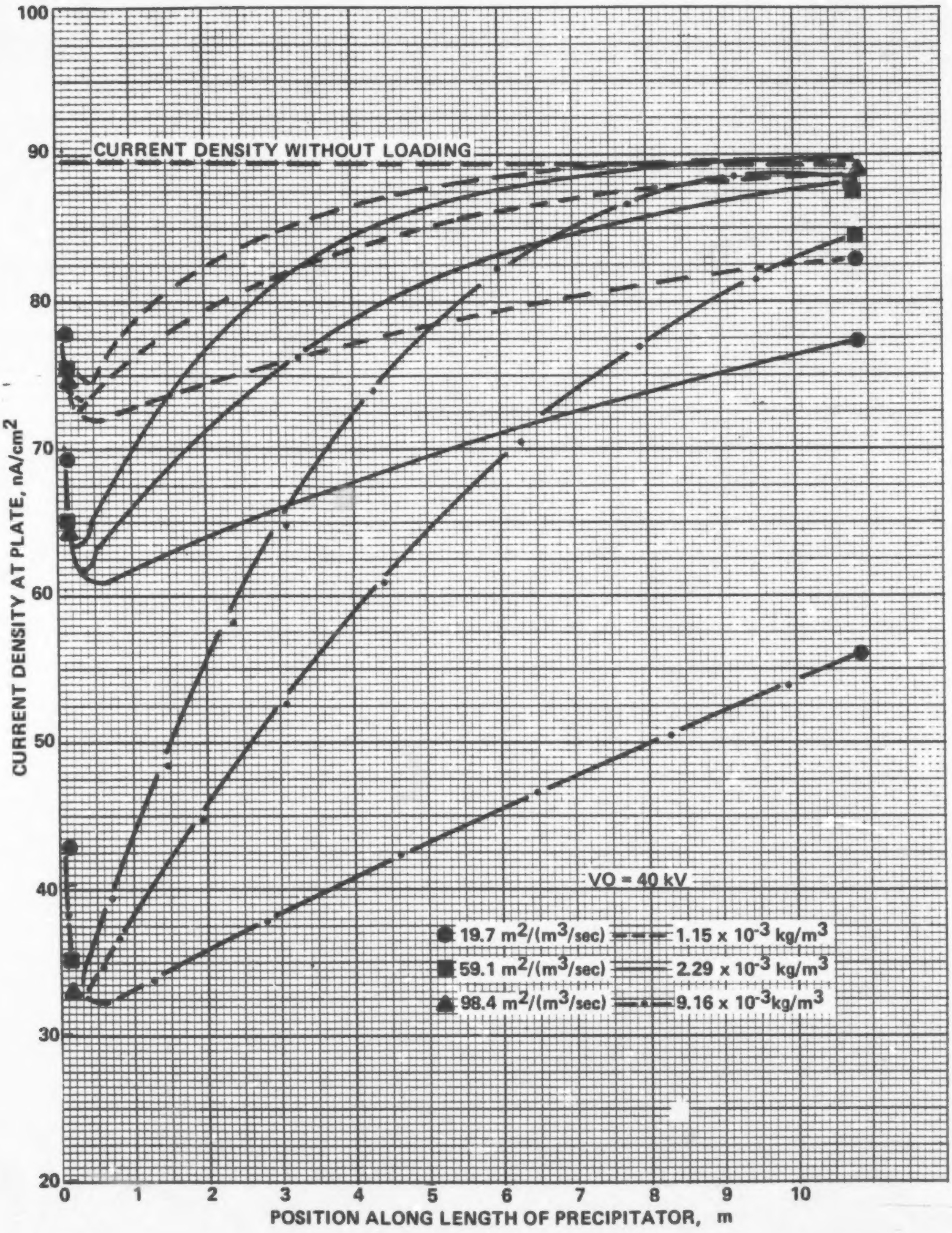


Figure 38. *Theoretical variation of average current density at the plate with precipitator length for different specific collection areas and inlet mass loadings at 40 kV.*

and charged particles are collected, it should reach a minimum and begin to increase.

Figures 39-42 show results obtained by dividing the precipitator into four electrical sections and calculating voltage-current characteristics for each section. The calculations are for an inlet mass loading of 9.16×10^{-3} kg/m^3 and a range of specific collection areas. The curves indicate the effect of particulate space charge on the operating voltage-current characteristics in different electrical sections of the precipitator.

In Figure 43, the predictions of the model using this space charge scheme are compared with field test data from a full-scale precipitator with wire-duct geometry and the predictions of the model using the alternate space charge scheme based on equation (16). The figure also shows the effect of the roughness factor in determining current density and collection efficiency. The results indicate that the condition of the wire plays a very important role in the theoretical determination of voltage-current characteristics. A roughness factor of 0.9 yields an average operating current density of 25 nA/cm^2 at the operating voltage of 33 kV. The actual average operating current density was 20 nA/cm^2. The roughness factor could be adjusted to yield 20 nA/cm^2 but this refinement would probably not be meaningful due to the uncertainty in the ion mobility of the flue gas which was taken to be 2.2×10^{-4} m^2/V·sec at standard temperature and pressure. A roughness factor of 0.9 would not be unreasonable since the electrodes were known to be in good condition at the time of the test. If the wires are specked with dirt or scratched, then it is appropriate to use a roughness factor. However, if the wires are uniformly coated with a layer of dirt, then the effect is one of increasing the radius of the discharge electrode which has a different effect on the voltage-current characteristics.

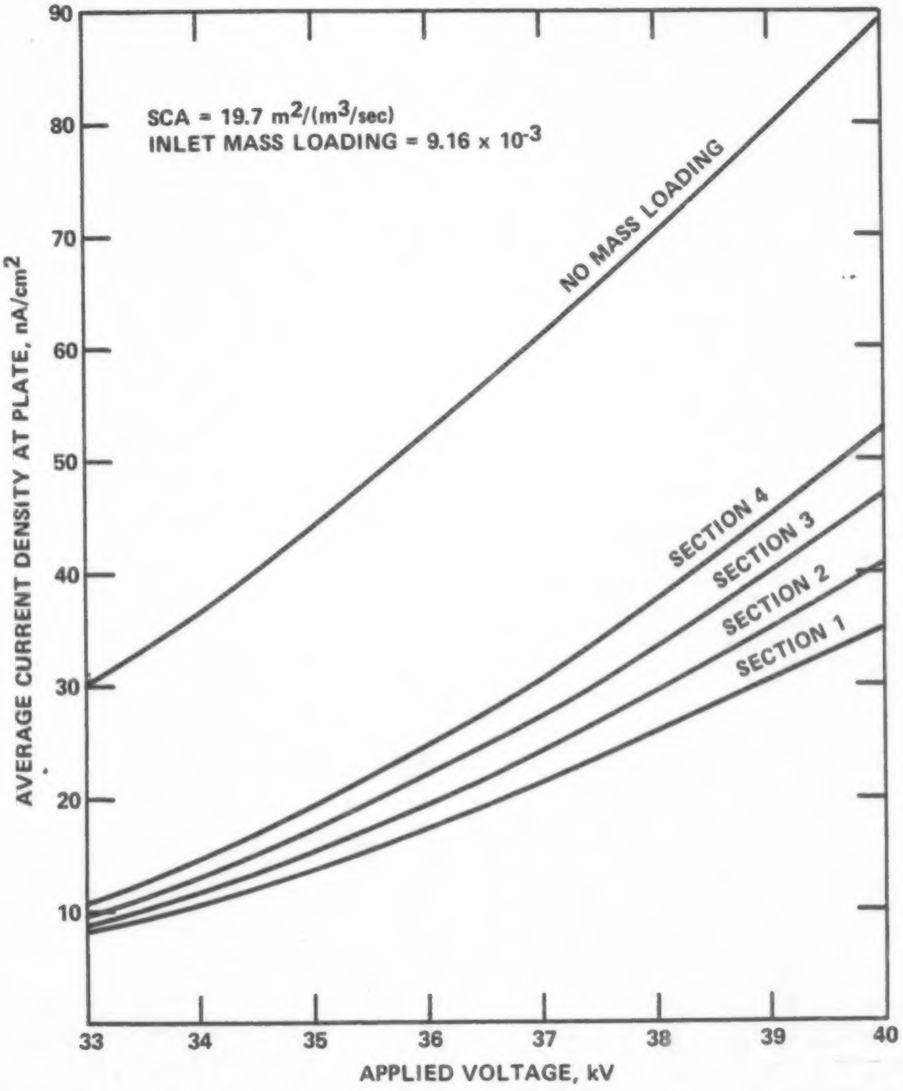


Figure 39. *Theoretical voltage-current curves for a specific collection area of 19.7 $m^2/(m^3/sec)$.*

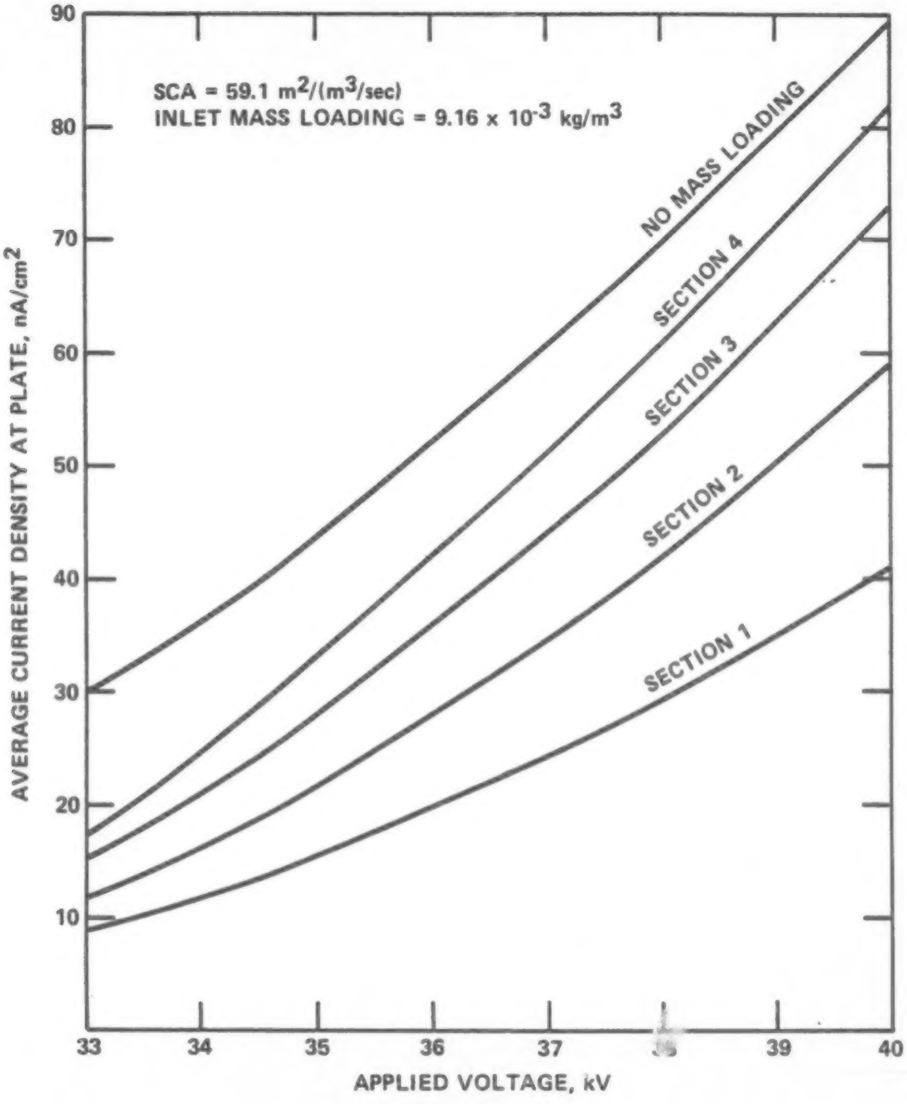


Figure 40. *Theoretical voltage-current curves for a specific collection area of 59.1 $m^2/(m^3/sec)$.*

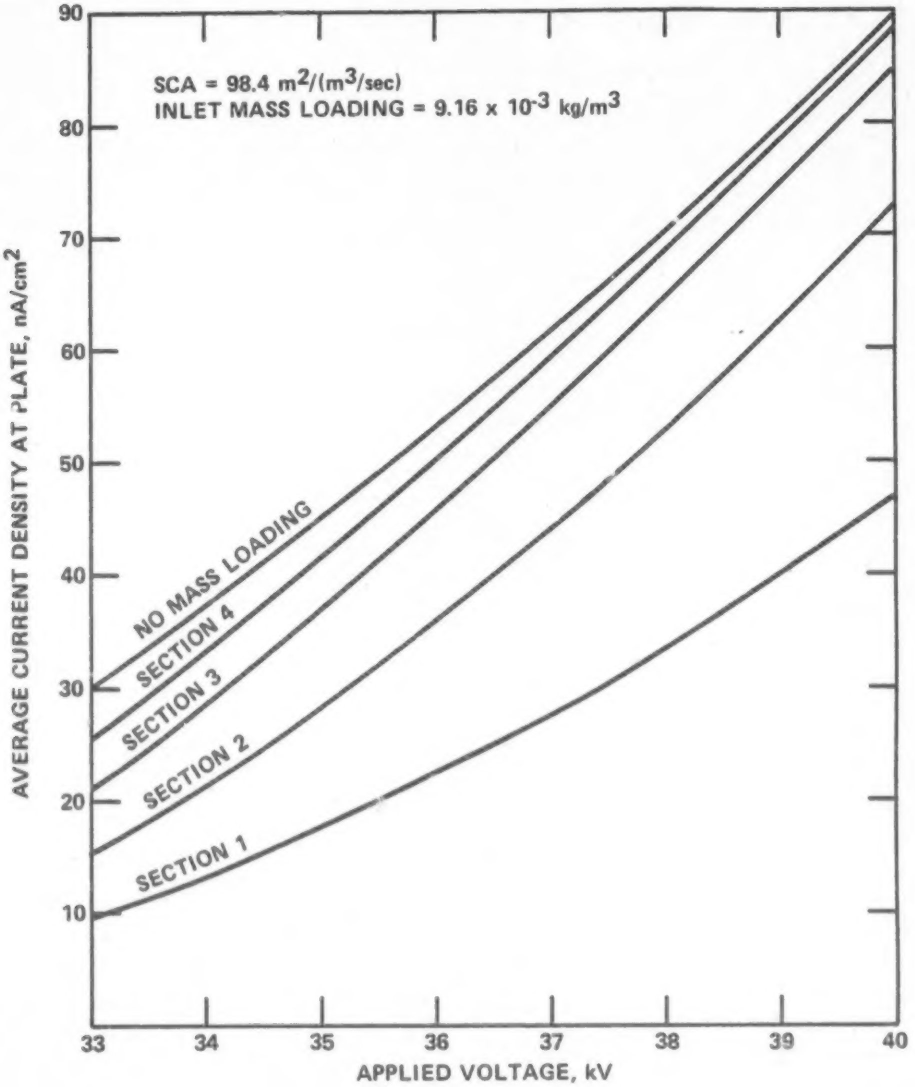


Figure 41. *Theoretical voltage-current curves for a specific collection area of 98.4 $m^2/m^3/sec)$.*

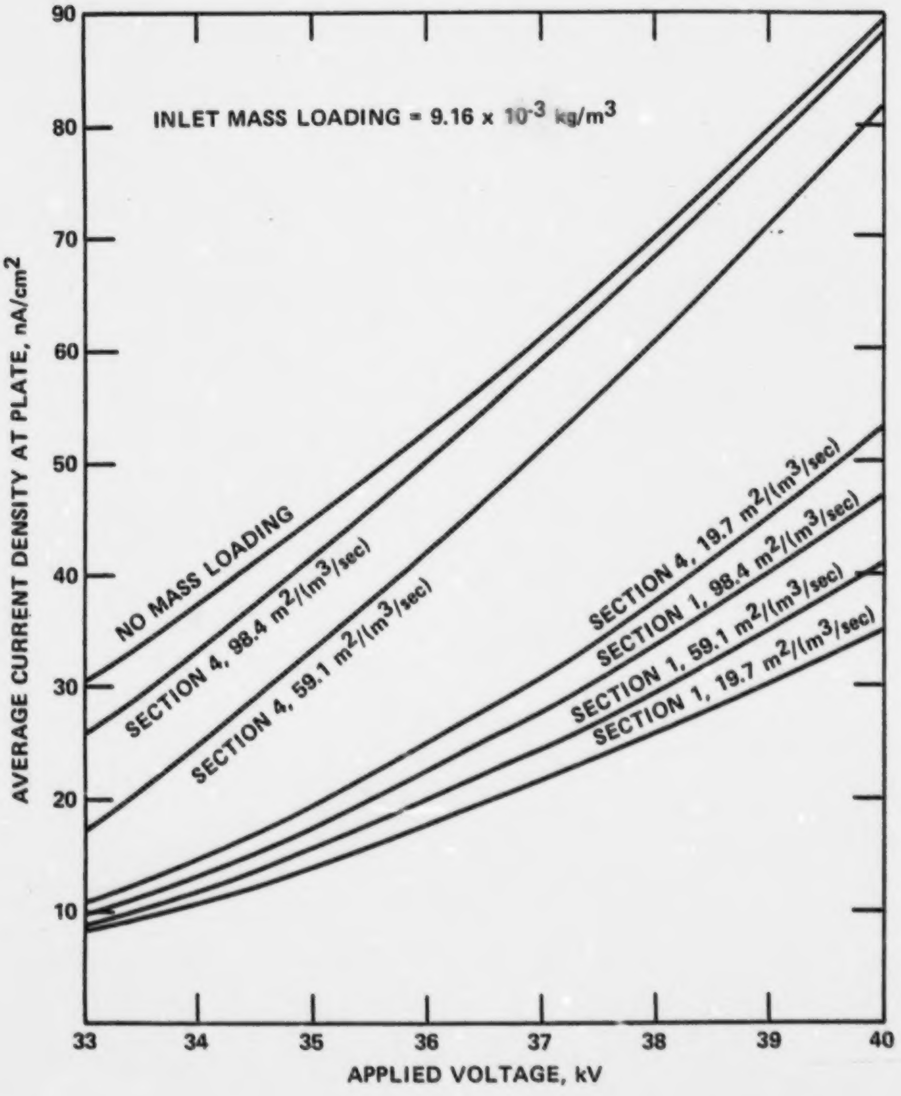


Figure 42. *Comparison of theoretical voltage-current curves for different specific collection areas.*

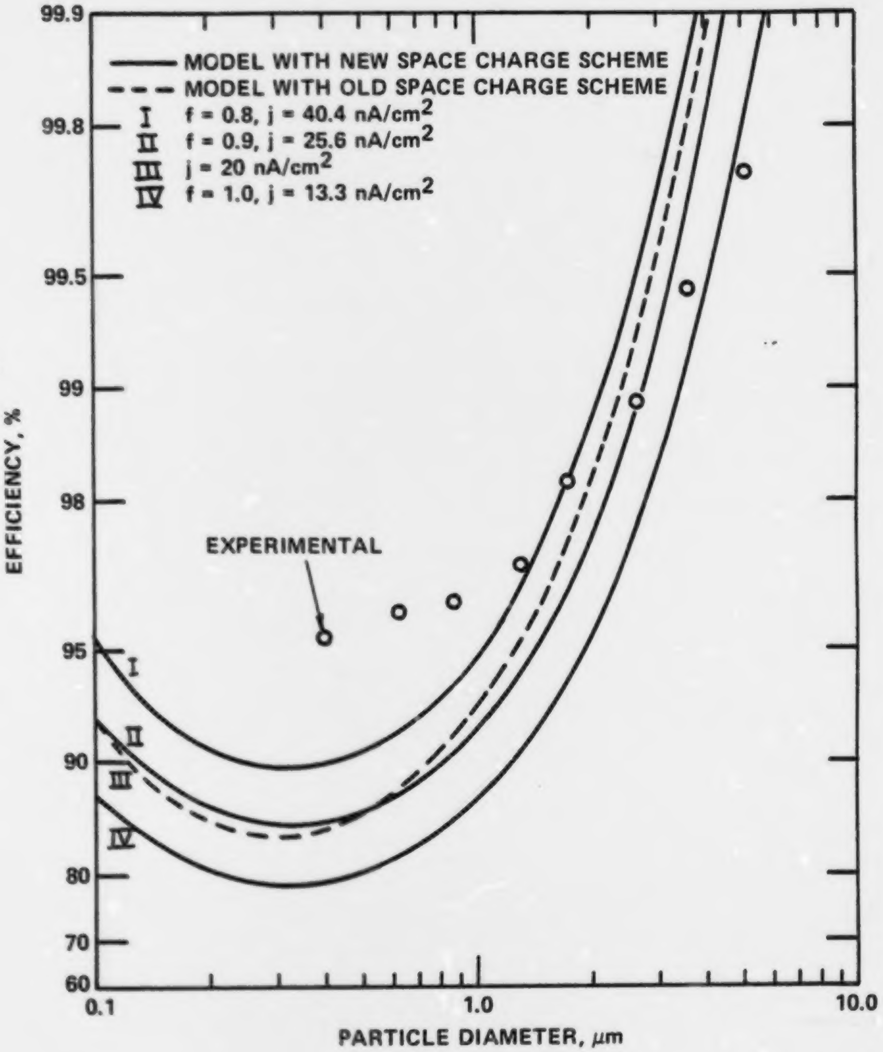


Figure 43. *Comparison of model predictions using the different space charge schemes with field test data from a full-scale precipitator. Model predictions are for unadjusted, no-rap efficiencies where* $\sigma_g = 0.25$ *and* $S = 0$.

APPENDIX B

DEFINITIONS OF VARIABLES USED IN THE MAIN PROGRAM AND SUBROUTINES

LIST OF VARIABLES, DEFINITIONS, AND UNITS FOR THE MAIN PROGRAM OF THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NWIRE - Number of wires per electrical section per gas passage in a particular electrical section

LTHICK - Thickness of the collected particulate layer in a particular increment of length (mm/min)

JPART - Current density due to particles in a particular increment of length (A/m^2)

JION - Current density due to ions in a particular increment of length (A/m^2)

LINC - Length of the increments taken in a particular linear electrical section (m)

NWS(I) - Number of wires per electrical section per gas passage for the different linear electrical sections

LINCS(I) - Lengths of the increments taken in the different linear electrical sections (ft)

VISKIP - Indicator which determines whether or not a dirty-gas voltage-current curve is calculated in each increment of length

VISAME - Indicator which determines whether or not a clean-gas voltage-current curve is calculated for each of the electrical sections or just the first electrical section

CHKSUM(K) - Fractional increase in charge from one increment to the next for the different particle sizes

DIAM(K) - Diameters of the different particle sizes (μm and m)

ONO(K) - Initial number of particles per cubic meter of gas in each particle size band ($\#/m^3$)

DXS(K) - Total number of particles removed per cubic meter of gas in each particle size band under ideal conditions and with no empirical corrections ($\#/m^3$)

XMV(K) - Effective migration velocities for the different particle sizes under ideal conditions and with no empirical corrections (m/sec)

PCNT(K) - Percentage or fraction by mass in the inlet particle size distribution of the different size bands (% and decimal)

RAD(K) - Radii of the different particle sizes (m)

CCF(K) - Cunningham correction factor for the different particle sizes

PRCU(L) - Cumulative percent by mass up to each particle size in the inlet particle size distribution (%)

LSECT(I) - Number of length increments in the different linear electrical sections

PS(I) - Gas pressure in the different electrical sections (atm)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

ATOTAL - Total collection plate area of the precipitator (m^2)

DD - Mass density of the particles (kg/m^3)

ETAO - Estimated or design overall mass collection efficiency (%)

DL - Inlet mass loading ($grains/ft^3$ and kg/m^3)

PL - Total electrical length of the precipitator (ft and m)

RHO - Resistivity of the collected particulate layer (ohm-cm and ohm-m)

NS - Number of different particle size bands in the inlet particle size distribution

ZMMDI - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMI - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

NONID - Number of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered

NRAPD - Number of rapping puff particle size distributions to be considered

TDK - Temperature of the gas in a given electrical section (°K)

NUMSEC - Number of linear electrical sections in the precipitator

NEFF - Indicator which determines whether the unadjusted, ideal or adjusted, no-rap efficiency is used to determine the mass reentrained due to rapping

NTEMP - Indicator which specifies whether the precipitator is cold or hot side

GFIT - Linear-correlation coefficient obtained in the lognormal fit of the inlet particle size distribution

VOL(K) - Total volume of particles per cubic meter of gas in the different size bands (m^3/m^3(gas))

XNO(K) - Number of particles per cubic meter of gas in each size band at the start of each increment ($\#/m^3$)

Q(K) - Charge on each particle size at the end of a particular increment (coul)

WS(K) - Total weight of material per cubic meter of gas removed in each size band in a particular increment (kg/m^3)

ITL(M) - Identifying label for the calculations

DW(J) - Amount of material removed per increment on a total weight basis (kg)

AS(I) - Collection plate areas for the different linear electrical sections (m^2)

VOS(I) - Applied voltages for the different linear electrical sections (V)

TCS(I) - Total current for the different linear electrical sections (A)

WLS(I) - Total wire length for the different linear electrical sections (ft^2)

ACS(I) - Corona wire radii for the different linear electrical sections (in.)

BS(I) - Wire-to-plate spacing for the different linear electrical sections (in.)

SYS(I) - One-half the wire-to-wire spacing for the different linear electrical sections (in.)

VGS(I) - Gas volume flow rate for the different linear electrical sections (ft^3/min)

VGASS(I) - Gas velocity for the different linear electrical sections (ft/sec)

TEMPS(I) - Gas temperature for the different linear electrical sections (°F)

VISS(I) - Gas viscosity for the different linear electrical sections (kg/m-sec)

QSAT(K) - Saturation charge for the different particle sizes (coul)

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

E - Elementary charge unit (coul)

EPSO - Permittivity of free space (coul^2/nt-m^2)

PI - Value of the constant π

ERAVG - Average electric field used for particle charging (V/m)

BC - Boltzmann's constant (J/°K)

TEMP - Gas temperature in a particular linear electrical section (°R)

EPS - Relative dielectric constant of the particles

VAVC - Average velocity of the ions (m/sec)

OLDQ(K) - Charge on the different particle sizes in the increment prior to the one under consideration (coul)

OLDXNO(K) - Number of particles per cubic meter of gas in each size band at the start of the increment prior to the one under consideration (#/m^3)

RFS(I) - Roughness factor for the corona wires in the different linear electrical sections

START1(I) - Specified initial current density at which the calculation of a voltage-current curve starts in a given electrical section and the initial current density increment size (A/m^2)

START2(I) - Specified increment in current density which is used in place of START1(I) when the JI1-th point on the voltage-current curve is reached (A/m^2)

START3(I) - Specified increment in current density which is used in place of START2(I) when the JI2-th point on the voltage-current curve is reached (A/m^2)

VSTAR(I) - Estimate of the applied voltage corresponding to the first point on the voltage-current curve as defined by START1(I) (V)

XDC(J,K) - Charge on each particle size at the end of each increment (coul)

EAVG(N) - Average electric fields for particle charging in subincremental lengths (V/m)

CHFID(N) - Average free ion densities for particle charging in subincremental lengths (#/m^3)

ECOLL(N) - Average electric fields at the plate in subincremental lengths (V/m)

ECLEAN(N) - Average electric fields at the plate for clean gas in subincremental lengths (V/m)

ENDPT(L) - Particle diameters in the inlet cumulative percent by mass distribution (μm and m)

NENDPT - Number of particle diameters in the inlet cumulative percent by mass distribution

ARD50(II) - Rapping puff mass median diameters (μm)

ARSIGM(II) - Rapping puff geometric standard deviations

ASNUCK(JJ) - Fractions of gas sneakage and/or particle reentrainment without rapping

AZNUMS(JJ) - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur

AZIGGY(JJ) - Normalized standard deviations of the gas velocity distribution

VCOOP(KK,LL) - Values at different grid points of the electric potential in a wire-plate geometry under conditions of no space charge (V)

TMFP - Ionic mean free path multiplied by a factor (m)

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

NPRINT - Indicator which designates when to print certain sectionalized data

NSECT - Indicator which keeps track of which electrical section the calculation is in

SLNGTH - Length of a particular electrical section (m)

A - Collection plate area of a particular linear electrical section (m^2)

VO - Applied voltage in a particular linear electrical section (V)

TC - Total current in a particular linear electrical section (A)

B - Wire-to-plate spacing in a particular linear electrical section (m)

AC - Corona wire radius in a particular linear electrical section (m)

WL - Total wire length in a particular linear electrical section (m)

CL - Total current per length of corona wire in a particular linear electrical section (A/m)

CD - Average current density at the plate in a particular linear electrical section (A/m^2)

ET - Average electric field in the deposited particulate layer in a particular linear electrical section (V/m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section (m)

VGAS - Gas velocity in a particular linear electrical section (m/sec)

P - Gas pressure in a particular linear electrical section (atm)

VIS - Gas viscosity in a particular linear electrical section (kg/m-sec)

W - Total weight of particles per second passing into a particular linear electrical section (kg/sec)

XPI - Overall mass collection efficiency per increment based on the estimated or design efficiency (%)

RIOVR - Ratio of the ionic space charge density to the total space charge density

EPLT - Absolute value of the average electric field at the plate in a particular length increment (V/m)

AFID - Average reduced free ion density for particle charging in a particular length increment ($\#/m^3$)

XCD - Average current density at the plate in a particular length increment (nA/cm^2)

ZMD - Interpolated mass median diameter of the collected particulate layer (m)

WT - Total weight of material per cubic meter of gas removed in all particle size bands in a given length increment (kg/m^3)

I - Index which runs over the different incremental lengths in its major usage

ROVRI - Ratio of the total space charge density to the ionic space charge density

NCALC - Indicator which determines whether to use equation (12) for particle charging or the sum of the classical field and diffusion charges

NI - Number of subincremental lengths into which the incremental length is divided

VRATIO - Ratio of the peak applied voltage to the average for use in particle charging

NF - Number of increments taken along the length of the precipitator

NREAD - Indicator which specifies the unit number of the input device for reading data into the program

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

SCOREF - Overall mass collection efficiency under no-rap + rap conditions (%)

CZMDL - Fitted log-normal mass median diameter of the outlet particle size distribution under no-rap + rap conditions (μm)

CSIGMO - Fitted log-normal geometric standard deviation of the outlet particle size distribution under no-rap + rap conditions

NRUN - Indicator that specifies which set of nonideal conditions is under consideration

SNUCK - Particular value of ASNUCK(JJ)

ZIGGY - Particular value of AZIGGY(JJ)

RMMD - Particular value of ARD50(II)[μm]

RSIGMA - Particular value of ARSIGM(II)

LK - Indicator which determines whether or not the input data are printed at a certain location in the program

DV - Total volume per cubic meter of gas occupied by particles [m^3(particles)/m^3(gas)]

NN - Number of increments in the Runge-Kutta integration of equation (12)

NUMINC - Number of increments in the Simpson's Rule integration over Θ in equation (12)

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

NDATA - Indicator which determines the type of data set that is to be read into the program

NEST - Indicator which specifies whether to use extensive calculations or estimation procedures in determining precipitator performance

NDIST - Indicator which specifies whether the user is to supply the inlet particle size distribution or the program is to calculate a log-normal distribution

NITER - Indicator which determines the maximum number of iterations over a loop that converges on overall mass efficiency or the number of iterations that will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions

IFINAL - Indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points

JI1 - Indicator which allows the initial increment size on current density in the calculation of the voltage-current curve to be changed after JI1-1 points are determined on the curve

JI2 - Indicator which allows the second increment size on current density in the calculation of the voltage-current curve to be changed after JI2-1 points are determined on the curve

US - Ion mobility at standard temperature and pressure (reduced ion mobility)

FPATH - Factor which scales the ion mean free path

EBD - Electrical breakdown strength of the gas near the collection electrode or the collected particulate layer (V/m)

NDSET - Counter which keeps track of the number of the particular set of nonideal conditions which is under consideration

D50 - Same as ZMMDI (μm)

SIGMAP - Same as SIGMI

SCHARG - Saturation charge number from the field charging equation

CHRFID - Average free ion density for particle charging ($\#/m^3$)

TIMEI - Initial value of time for particle charging (sec)

TIMEF - Final value of time for particle charging (sec)

V - Value of the quantity $[e^2/4\pi\varepsilon_0 akT]$ found in equation (12)

FACTRE - Value of the quantity $[\pi\tilde{v}a^2/2]$ found in equation (12) $[m^3/sec]$

RSIZE - Radius of a particular particle (m)

CNUMBR - Charge number of a particular particle at time TIMEF

J - Index which runs over different particle size bands

II - Index which runs over subincremental lengths

ITER - Counter which keeps track of the number of iterations which is limited by NITER

OLDQF(K) - Value of field charge on the different particle sizes at the end of a given increment or subincrement (coul)

OLDQT(K) - Value of diffusion charge on the different particle sizes at the end of a given increment or subincrement (coul)

SOLDQF(K) - Value of field charge on the different particle sizes at the start of an increment which must be saved for the iteration procedure over subincrements in a given increment (coul)

SOLDQT(K) - Value of diffusion charge on the different particle sizes at the start of an increment which must be saved for the iteration procedure over subincrements in a given increment (coul)

CMKS - Value of the quantity $[4\pi\varepsilon_0]$ found in equation (12) $[\mathrm{coul}^2/\mathrm{nt\text{-}m}^2]$

KA - Index which runs over the different linear electrical sections

ZWT - Total weight of material per cubic meter of gas removed up to a given increment ($\mathrm{kg/m}^3$)

RATIO - Value of the quantity [(K-1)/(K+2)] found in the particle charging equations

G - Value of the quantity [K+2] found in the particle charging equations

INDEX - Indicator which keeps track of how many increments the calculation is into a particular linear electrical section

NCOOP - Indicator which allows certain calculations to be made only at the start of a new linear electrical section

SX - Wire-to-plate spacing in a particular linear electrical section (m)

RF - Roughness factor for the discharge wires in a particular linear electrical section

START - Particular value of START1(I) $[A/m^2]$

DSTART - Particular value of START2(I) $[A/m^2]$

CSTART - Particular value of START3(I) $[A/m^2]$

VSTART - Particular value of VSTAR(I) [V]

ZMFP - Ionic mean free path (m)

VAVG - Average velocity of the ions (cm/sec)

VC - Value of the quantity $[e^2/kT]$ found in the charging equations (coul/V)

FACTRC - Value of the quantity $[\pi\tilde{v}/2]$ found in the charging equations (m/sec)

COEFFC - Value of the quantity $[e\pi b]$ found in the charging equations (coul-m^2/V-sec)

TINC - Time interval for the gas to travel one increment (sec)

DTINC - Time interval for the gas to travel one subincrement (sec)

L - Index which runs over the different particle size bands

R - Value of the quantity $[eE_0/kT(K+2)]$ found in equation (12) $[m^{-1}]$

RR - Value of the quantity $[eE_0/kT]$ found in equation (12) $[m^{-1}]$

RG - Same as RR

VW - Operating applied voltage corresponding to a specified current density (V)

UEQ - Effective charge carrier mobility (m^2/V-sec)

NEC - Indicator which determines whether or not the average current density, average electric field, and average electric field at the plate are to be calculated in the subincremental lengths

AEPLT - Average electric field at the plate in a particular increment (V/m)

ACDNTY - Average current density at the plate in a particular increment (A/m^2)

NZ - Index which runs over subincremental lengths

CDCLN - Average current density at the plate when the gas is clean (A/m^2)

USUM - Sum of effective charge carrier mobilities over the subincremental lengths in a particular incremental length (m^2/V-sec)

WSSUM - Total weight of material per cubic meter of gas removed in a particular size band in a particular subincrement (kg/m^3)

RHOSUM - Sum of the ratio of the ionic space charge to the total space charge over the subincremental lengths in a particular incremental length

SW - Cumulative sum of estimated amount of material removed per second in successive length increments (kg/sec)

OROVRI - Ratio of total charge density to ionic charge density in increment prior to the one the calculation is in

XS - Computed value of the exponential argument in the Deutsch equation for the estimated or design overall mass collection efficiency

ETAPF - Overall mass collection fraction per increment based on the estimated or design efficiency

FID - Average free ion density (#/m^3)

AVGFID - Average reduced free ion density for particle charging (#/cm^3)

PROT - Total charge density due to particles that remain after passing through a given increment (coul/m^3)

SERAVG - Average electric field in a particular increment (V/m)

XIPC - Initial value of charge number on a given particle size at the start of a new increment

H - Increment size for the Runge-Kutta integration of equation (12) [sec]

DCONST - Value of the quantity $[(K-1)a^3/(K+2)]$ found in equation (12) $[m^3]$

CONST - Value of the quantity $[2(K-1)a^3E_0/(K+2)]$ found in equation (12) $[V\text{-}m^2]$

S - Value of the quantity $[3a]$ found in equation (12) [m]

ECONST - Value of the quantity $[3eE_0a/kT(K+2)]$ found in equation (12)

FCONST - Value of the quantity $[(K-1)eE_0a^3/kT(K+2)]$ found in equation (12) $[m^2]$

COEFF - Value of the quantity $[bqs/4\varepsilon_0]$ found in equation (12) $[m^3/sec]$

CTIME - Time at the end of a given increment (sec)

EMV(K) - Unadjusted, ideal migration velocities for the different particle sizes in a given increment (m/sec)

X - Exponent used in the Deutsch equation to determine the unadjusted, ideal collection fractions for the different particle sizes in a given increment

EFF - Unadjusted, ideal collection fraction for a given particle size band in a given increment

DXNO - Number of particles per cubic meter of gas removed from a given particle size band in a given increment $(\#/m^3)$

DNSION - Ion density in the absence of particles $(\#/m^3)$

DELTNP - Number density of charges transferred from ions to particles in a given subincremental length $(\#/m^3)$

SUMMOB - Weighted summation of particle mobilities $(m^2/V\text{-}sec/m^3)$

PNUM - Total number of particles per unit volume of gas entering a given subincremental length $(\#/m^3)$

RHOP - Total average particulate charge density in a given subincremental length $(coul/m^3)$

TCHRG - Average particle charge density for a given particle size in a given subincremental length $(coul/m^3)$

PMOB - Weighted particulate mobility in a given subincremental length (m^2/V-sec)

TDNSP - Total average particulate charge number density in a given subincremental length (#/m^3)

RDNSI - Average reduced ion density in a given subincremental length (#/m^3)

SUMCD - Sum of the average current densities at the plate from the different increments in a particular linear electrical section (A/m^2)

SUMVO - Sum of the applied voltages from the different increments in a particular linear electrical section (V)

SKIP - Electric field at the plate in the increment prior to the one the calculation is in (V/m)

SIGMA - Difference between the ratio of the total space charge density to the ionic space charge density in the (I+1)-th and I-th increments

VERGE - Converged value of the space charge density at the wire in calculating the electric field at the plate (coul/m^3)

ZTM - Cumulative sum of the weight of material per cubic meter of gas collected up to a given particle size in a given increment (kg/m^3)

CZA - Ratio of the partial sum of the weight of dust removed per cubic meter of gas up the K-th particle size in a given increment to the total weight of dust removed per cubic meter of gas in a given increment

CZB - Ratio of the partial sum of the weight of dust removed per cubic meter of gas up to the (K-1)-th particle size in a given increment to the total weight of dust removed per cubic meter of gas in a given increment

TL1 - Difference between CZA and CZB for use in interpolating to find the mass median diameter of the collected dust

TL2 - Difference between 0.50 and CZB for use in interpolating to find the mass median diameter of the collected dust

KJ - Index which runs simultaneously with the index which runs over the different particle sizes and keeps track of the (K-1)-th particle size

ETC - Ideal, unadjusted overall mass collection efficiency for the entire precipitator (%)

DIFF - Difference between the calculated ideal, unadjusted overall mass collection efficiency and the estimated value

NRAP - Indicator used to specify whether dynamic rapping will be used and if so, what data will be printed

MODL - Indicator used to specify regular model, metric model, internal data set, or V-I curve generator

NOPRNT - Indicator used to suppress printing of charging information and certain opacity information

PATHL - Pathlength over which opacity is calculated (ft or m)

NCOMPS - Number of indices of refraction for which opacity is calculated

NWAVES - Number of wavelengths at which opacity is calculated

NLAMDA - Number of wavelength increments for variable composition

NINT - SCA counter for the internal data set

NREEN - Dynamic rapping indicator which marks the first loop through the rapping cycle so that rapping data may be read

LREEN - Dynamic rapping indicator which causes the initialization of several accumulators

LOOPR - Dynamic rapping indicator which marks the end of the rapping cycle and returns the precipitator model to its normal processing sequence

ICYC - Indicator which specifies which initial values are used for the potential grid in subroutine EFLD1

RAPDST - Array containing the number of particles in each size band per cubic meter of gas which are reintroduced into the gas flow in each increment of the precipitator by rapping ($\#/m^3$)

ICOOP - Indicator which specifies which initial values are used for the potential grid in subroutine EFLD1

NSCT - Increment counter

WREEN - Total weight of particles per second passing into a precipitator increment due to rapping (kg/sec)

RELD - Relative air density

ROC - Radius of corona wires (cm)

EORO - Product of the corona starting electric field and the wire radius

VSTR(K,J,NSCT) - Storage register for potential on grid from each increment

THICK(I) - Dust layer thickness in each increment

DCONST - Value of the quantity $[\frac{(K-1)}{(K+2)} a^3]$ found in equation (12) $[m^3]$

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE PRTINP USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

LK - Indicator which determines whether or not the input data are printed at a certain location in the program

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

NDSET - Counter which keeps track of the number of the particular set of nonideal conditions which is under consideration

DL - Inlet mass loading (kg/m^3)

DLB - Inlet mass loading ($grains/ft^3$)

PL - Total electrical length of the precipitator (m)

PLB - Total electrical length of the precipitator (ft)

RHO - Resistivity of the collected particulate layer (ohm-m)

RHOCGS - Resistivity of the collected particulate layer (ohm-cm)

NCARD - Counter which keeps track of the number of each successive imput data card

NENDPT - Number of particle diameters in the inlet cumulative percent by mass distribution

NDATA - Indicator which determines the type of data set that is to be read into the program

ITL(M) - Identifying label for the calculations

NEST - Indicator which specifies whether to use extensive calculations or estimation procedures in determining precipitator performance

NDIST - Indicator which specifies whether the user is to supply the inlet particle size distribution or the program is to calculate a log-normal distribution

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

NITER - Indicator which determines the maximum number of iterations over a loop that converges on overall mass efficiency or the number of iterations that will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions

NCALC - Indicator which determines whether to use equation (12) for particle charging or the sum of the classical field and diffusion charges

NRAPD - Number of rapping puff particle size distributions to be considered

NEFF - Indicator which determines whether the unadjusted, ideal or adjusted, no-rap efficiency is used to determine the mass reentrained due to rapping

NTEMP - Indicator which specifies whether the precipitator is cold or hot side

NONID - Number of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered

NN - Number of increments in the Runge-Kutta integration of equation (12)

NUMINC - Number of increments in the Simpson's Rule integration over Θ in equation (12)

IFINAL - Indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points

JI1 - Indicator which allows the initial increment size on current density in the calculation of the voltage-current curve to be changed after JI1-1 points are determined on the curve

JI2 - Indicator which allows the second increment size on current density in the calculation of the voltage-current curve to be changed after JI2-1 points are determined on the curve

VISKIP - Indicator which determines whether or not a dirty-gas voltage-current curve is calculated in each increment of length

VISAME - Indicator which determines whether or not a clean-gas voltage-current curve is calculated for each of the electrical sections or just the first electrical section

ETAO - Estimated or design overall mass collection efficiency (%)

DD - Mass density of the particles (kg/m^3)

EPS - Relative dielectric constant of the particles

VRATIO - Ratio of the peak applied voltage to the average for use in particle charging

US - Ion mobility at standard temperature and pressure (reduced ion mobility)

FPATH - Factor which scales the ion mean free path

EBD - Electrical breakdown strength of the gas near the collection electrode or the collected particulate layer (V/m)

ARD50(II) - Rapping puff mass median diameters (μm)

ARSIGM(II) - Rapping puff geometric standard deviations

ASNUCK(JJ) - Fractions of gas sneakage and/or particle reentrainment without rapping

AZIGGY(JJ) - Normalized standard deviations of the gas velocity distribution

AZNUMS(JJ) - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur

NDCARD - Indicator which determines how the arrays ENDPT(L) and PRCU(L) should be printed

ENDPT(L) - Particle diameters in the inlet cumulative percent by mass distribution (μm and m)

D50 - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMAP - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

PRCU(L) - Cumulative percent by mass up to each particle size in the inlet particle size distribution (%)

NUMSEC - Number of linear electrical sections in the precipitator

LSECT(I) - Number of length increments in the different linear electrical sections

AS(I) - Collection plate areas for the different linear electrical sections (m^2)

VOS(I) - Applied voltages for the different linear electrical sections (V)

TCS(I) - Total current for the different linear electrical sections (A)

WLS(I) - Total wire length for the different linear electrical sections (ft^2)

ACS(I) - Corona wire radii for the different linear electrical sections (in.)

BS(I) - Wire-to-plate spacing for the different linear electrical sections (in.)

NWS(I) - Number of wires per electrical section per gas passage for the different linear electrical sections

SYS(I) - One-half the wire-to-wire spacing for the different linear electrical sections (in.)

VGS(I) - Gas volume flow rate for the different linear electrical sections (ft^3/min)

VGASS(I) - Gas velocity for the different linear electrical sections (ft/sec)

TEMPS(I) - Gas temperature for the different linear electrical sections (°F)

PS(I) - Gas pressure in the different electrical sections (atm)

VISS(I) - Gas viscosity for the different linear electrical sections (kg/m-sec)

LINCS(I) - Lengths of the increments taken in the different linear electrical sections (ft)

RFS(I) - Roughness factor for the corona wires in the different linear electrical sections

START1(I) - Specified initial current density at which the calculation of a voltage-current curve starts in a given electrical section and the initial current density increment size (A/m^2)

START2(I) - Specified increment in current density which is used in place of START1(I) when the JI1-th point on the voltage-current curve is reached (A/m^2)

START3(I) - Specified increment in current density which is used in place of START2(I) when the JI2-th point on the voltage-current curve is reached (A/m^2)

VSTAR(I) - Estimate of the applied voltage corresponding to the first point on the voltage-current curve as defined by START1(I) (V)

NRAP - Indicator used to specify whether dynamic rapping will be used and if so, what data will be printed

MODL - Indicator used to specify regular model, metric model, internal data set, or V-I curve generator

NOPRNT - Indicator used to suppress printing of charging information and certain opacity information

PATHL - Pathlength over which opacity is calculated (ft or m)

NCOMPS - Number of indices of refraction for which opacity is calculated

NWAVES - Number of wavelengths at which opacity is calculated

NLAMDA - Number of wavelength increments for variable composition

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE SPCHG1 USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

I - Index which runs over the incremental lengths

SW - Cumulative sum of estimated amount of material removed per second in successive length increments (kg/sec)

ROVRI - Ratio of the total space charge density to the ionic space charge density

OROVRI - Ratio of total charge density to ionic charge density in increment prior to the one the calculation is in

ETAO - Estimated overall mass collection efficiency (%)

XS - Computed value of the exponential argument in the Deutsch equation for the estimated overall mass collection efficiency

LINC - Length of the increments taken in a particular linear electrical section (m)

PL - Total electrical length of the precipitator (m)

ETAPF - Overall mass collection fraction per increment based on the estimated efficiency

W - Total weight of particles per second passing into a particular linear electrical section (kg/sec)

DW(J) - Amount of material removed per increment on a total weight basis (kg)

CD - Average current density at the plate in a particular linear electrical section (A/m^2)

E - Elementary charge unit (coul)

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

ERAVG - Average electric field used for particle charging (V/m)

FID - Average free ion density (#/m^3)

SUM - Total particulate charge density in a given increment based on saturation charges (coul/m^3)

NS - Number of different particle size bands in the inlet particle size distribution

L - Index which runs over the different particle size bands

QSAT(L) - Saturation charge for the different particle sizes (coul)

XNO(L) - Number of particles per cubic meter of gas in each size band at the start of each increment (#/m^3)

LSECT(I) - Number of length increments in the different linear electrical sections

NSECT - Indicator which keeps track of which electrical section the calculation is in

TC - Total current in a particular linear electrical section (A)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

ZC - Ratio of the particulate charge density to the ionic charge density (ratio of 200 times the particulate current to the total current)

AFID - Average reduced free ion density for particle charging in a particular length increment (#/m^3)

AVGFID - Average reduced free ion density for particle charging (#/cm^3)

XCD - Average current density at the plate in a particular length increment (nA/cm^2)

UEQ - Effective charge carrier mobility (m^2/V-sec)

XPI - Overall mass collection efficiency per increment based on the estimated efficiency (%)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE SPCHG2 USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

I - Index which runs over the incremental lengths

ETAO - Design overall mass collection efficiency (%)

XS - Computed value of the exponential argument in the Deutsch equation for the design overall mass collection efficiency

LINC - Length of the increments taken in a particular linear electrical section (m)

PL - Total electrical length of the precipitator (m)

ETAPF - Overall mass collection fraction per increment based on the design efficiency

DELTNP - Number density of charges transferred from ions to particles in a given subincremental length ($\#/m^3$)

SUMMOB - Weighted summation of particle mobilities ($m^2/V\text{-}sec/m^3$)

PNUM - Total number of particles per unit volume of gas entering a given subincremental length ($\#/m^3$)

RHOP - Total average particulate charge density in a given subincremental length ($coul/m^3$)

J - Index which runs over the different particle size bands

XNO(J) - Number of particles per cubic meter of gas in each size band at the start of each increment ($\#/m^3$)

XDC(I,J) - Charge on each particle size at the end of each increment (coul)

TCHRG - Average particle charge density for a given particle size in a given subincremental length ($coul/m^3$)

CCF(J) - Cunningham correction factor for the different particle sizes

VIS - Gas viscosity in a particular linear electrical section (kg/m-sec)

RAD(J) - Radii of the different particle sizes (m)

DIFF - Difference between the charge on a given particle size in the (I+1)-th and I-th increments (coul)

II - Index which runs over the subincremental lengths

Q(J) - Charge on each particle size at the end of a particular increment (coul)

OLDQ(J) - Charge on the different particle sizes in the increment prior to the one under consideration (coul)

PMOB - Weighted particulate mobility in a given subincremental length (m^2/V-sec)

TDNSP - Total average particulate charge number density in a given subincremental length (#/m^3)

CHFID(II) - Average free ion densities for particle charging in subincremental lengths (#/m^3)

DNSION - Ion density in the absence of particles (#/m^3)

RDNSI - Average reduced ion density in a given subincremental length (#/m^3)

PIR - Ratio of the total charge density which can be accepted by particles in a given subincrement to the available free ion density

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

AFID - Average reduced free ion density for particle charging in a particular length increment (#/m^3)

AVGFID - Average reduced free ion density for particle charging (#/cm^3)

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

E - Elementary charge unit (coul)

UEQ - Effective charge carrier mobility (m^2/V-sec)

RIOVR - Ratio of the ionic space charge density to the total space charge density

XPI - Overall mass collection efficiency per increment based on the design efficiency (%)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE EFLD1 USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

VO - Applied voltage (negative value used in calculations) [V]

PI - Value of the constant π

EPSO - Permittivity of free space ($\text{coul}^2/\text{nt-m}^2$)

AC - Radius of the corona wires (m)

RO - Radius of the corona wires (m)

TDK - Temperature of the gas stream (°K)

P - Pressure in the gas stream (atm)

CD - Average current density at the plate (A/m^2)

UEQ - Effective charge carrier mobility ($\text{m}^2/\text{V-sec}$)

VERGE - Initial estimate of the space charge density at the corona wire to start the calculation of the electric field at the plate (coul/m^3)

QZERO - Space charge density at the corona wire (coul/m^3)

I - Index which runs over grid points in the x-direction

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

J - Index which runs over grid points in the y-direction

D3 - Value of the quantity $[2a_y b_{i,j}]$ for interior points in the grid ($\text{m}^3/\text{V-sec}$)

D4 - Value of the quantity $[2a_x a_y b_{i,j}]$ for interior points in the grid ($\text{m}^4/\text{V-sec}$)

D5 - Value of the quantity $[-\varepsilon_0(E_x(2a_y b_{i,j} - a_y b_{i-1,j}) + E_y(2a_x b_{i,j} - a_x b_{i,j-1}))]$ for interior points in the grid ($\text{coul}^2/\text{nt-sec}$)

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

MOBILT(I,J) - Array containing the values of effective charge carrier mobility at the different grid points (m^2/V-sec)

MAXJ - Upper limit that the calculated average current density at the plate cannot exceed (A/m^2)

MINJ - Lower limit that the calculated average current density at the plate cannot fall below (A/m^2)

NX1 - Number of grid intervals in the x-direction for the numerical calculations of electrical conditions

NY1 - Number of grid intervals in the y-direction for the numerical calculations of electrical conditions

SX - Wire-to-plate spacing in a particular linear electrical section (m)

AX - Interval size in the x-direction (m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section (m)

AY - Interval size in the y-direction (m)

AXS - Value of the quantity $[a_x{}^2]$ (m^2)

AYS - Value of the quantity $[a_y{}^2]$ (m^2)

ASP - Value of the quantity $[(a_x{}^2+a_y{}^2)/\varepsilon_0]$ (m^4-nt/coul^2)

ASS - Value of the quantity $[1/2(a_x{}^2+a_y{}^2)]$ (m^{-2})

Z - Counter which keeps track of the number of times the calculation iterates due to lack of convergence in the average current density at the plate

VCOOP(I,J) - Array containing the values of electric potential given equation (26) at the different grid points (V)

V(I,J) - Array containing the value of the electric potential at each point in the grid during an iteration (V)

IZ - Same as Z

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

LL - Counter which keeps track of the number of times the calculation iterates due to lack of convergence in the electric potential at each point in the grid

RHO(I,J) - Array containing the value of the space charge density at each point in the grid during an iteration (coul/m^3)

EX(I,J) - Array containing the value of the component of the electric field intensity perpendicular to the plates at each point in the grid during an iteration (V/m)

EY(I,J) - Array containing the value of the component of the electric field intensity parallel to the plates at each point in the grid during an iteration (V/m)

Q1 - Value of the quantity $[2b_{i,1}]$ along the line AD where $b_{i,j}$ is the effective charge carrier mobility which is a function of position (m^2/V-sec)

Q2 - Value of the quantity $[2b_{i,1}a_x]$ along the line AD (m^3/V-sec)

Q3 - Value of the quantity $[2b_{i,1}a_y]$ along the line AD (m^3/V-sec)

Q4 - Value of the quantity $[2b_{i,1}a_xa_y]$ along the line AD (m^4/V-sec)

Q5 - Value of the quantity $[-\varepsilon_0 E_x(2b_{i,1}a_y - a_y b_{i-1,1})]$ along the line AD ($coul^2$/nt-sec)

Q6 - Value of the quantity $[\varepsilon_0^2 E_x^2(2b_{i,1}a_y - a_y b_{i-1,1})^2]$ along the line AD ($coul^4/nt^2$-sec^2)

Q7 - Value of the quantity $[4b_{i,1}^2 a_x a_y^2 \varepsilon_0 E_x \rho_{i-1,1}]$ along the line AD where $\rho_{i,j}$ is the space charge density at the different grid points ($coul^2$-m^2/V^2-sec^2)

Q8 - Value of the quantity $[-\sqrt{Q6+Q7}]$ along the line AD (coul-m/V-sec)

P1 - Value of the quantity $[2b_{i,j}]$ along the line AB (m^2/V-sec)

P2 - Value of the quantity $[2b_{i,j}a_x]$ along the line AB (m^3/V-sec)

P3 - Value of the quantity $[2b_{1,j}a_y]$ along the line AB (m^3/V-sec)

P4 - Value of the quantity $[2b_{1,j}a_x a_y]$ along the line AB (m^4/V-sec)

P5 - Value of the quantity $[-\varepsilon_0 E_y(2b_{1,j}a_x - a_x b_{1,j-1})]$ along the line AB ($coul^2/nt$-sec)

P6 - Value of the quantity $[\varepsilon_0{}^2 E_y{}^2(2b_{1,j}a_x - a_x b_{1,j-1})^2]$ along the line AB ($coul^4/nt^2$-sec^2)

P7 - Value of the quantity $[4b^2_{1,j}a_x{}^2 a_y \varepsilon_0 E_y \rho_{1,j-1}]$ along the line AB ($coul^2$-m^2/V^2-sec^2)

P8 - Value of the quantity $[-\sqrt{P6+P7}]$ along the line AB (coul-m/V-sec)

R1 - Value of the quantity $[2b_{i,NY}]$ along the line BC (m^2/V-sec)

R2 - Value of the quantity $[2b_{i,NY}a_x]$ along the line BC (m^3/V-sec)

R3 - Value of the quantity $[2b_{i,NY}a_y]$ along the line BC (m^3/V-sec)

R4 - Value of the quantity $[2b_{i,NY}a_x a_y]$ along the line BC (m^4/V-sec)

R5 - Value of the quantity $[-\varepsilon_0 E_x(2b_{i,NY}a_y - a_y b_{i-1,NY})]$ along the line BC ($coul^2/nt$-sec)

R6 - Value of the quantity $[\varepsilon_0{}^2 E_x{}^2(2b_{i,NY}a_y - a_y b_{i-1,NY})]$ along the line BC ($coul^4/nt^2$-sec^2)

R7 - Value of the quantity $[4b^2_{i,NY}a_x a_y^2 \varepsilon_0 E_x \rho_{i-1,NY}]$ along the line BC ($coul^2$-m^2/V^2-sec^2)

R8 - Value of the quantity $[-\sqrt{R6+R7}]$ along the line BC (coul-m/V-sec)

D1 - Value of the quantity $[2b_{i,j}]$ for interior points in the grid (m^2/V-sec)

D2 - Value of the quantity $[2a_x b_{i,j}]$ for interior points in the grid (m^3/V-sec)

D6 - Value of the quantity [D5·D5] ($coul^4/nt^2-sec^2$)

D7 - Value of the quantity [$4b^2_{i,j}a_x a_y \varepsilon_0 (a_y E_x \rho_{i-1,j} + a_x E_y \rho_{i,j-1})$] for interior points in the grid ($coul^2-m^2/V^2-sec^2$)

D8 - Value of the quantity [$-\sqrt{D6+D7}$] for interior points in the grid (coul-m/V-sec)

OLDV(I,J) - Array containing the value of the electric potential at each point in the grid during the previous iteration (V)

OLDRO(I,J) - Array containing the value of the space charge density at each point in the grid during the previous iteration ($coul/m^3$)

CDNSTY(I,J) - Array containing the value of current density at each point in the grid (A/m^2)

ACDNTY - Average current density at the plate (A/m^2)

EPLT - Sum of the values of the electric field intensity at the plate (V/m)

AEPLT - Average electric field at the plate (V/m)

VERGE - Converged value of the space charge density at the wire in calculating the electric field at the plate ($coul/m^3$)

ICYC - Indicator which specifies which initial values are used for potential grid

NSCT - Increment counter

ICOOP - Indicator which specifies which initial values are used for potential grid

VSTR(I,J,NSCT) - Storage register for V(I,J) from each increment

ITMAX - Maximum number of iterations allowed for convergence of potential across grid

IZMAX - Maximum number of iterations allowed for convergence on current density

ITER - Number of times calculation iterates without converging since last acceleration step

ECONV - Potential convergence criterion

IJMIN - Number of times the calculation iterates without converging before new acceleration step performed

ALPH - Damping factor included in dominant eigenvalue calculation to prevent instability

DV - Difference in potential from preceding to current iteration at each grid point

DVR - Normalized change in potential at each grid point

DVRM - Maximum normalized change in potential in this iteration

DXM - Norm of potential differences across grid used for calculating dominant eigenvalue

DXML - Value of DXM from preceding iteration

EIG1 - Dominant eigenvalue

EIGL - Dominant eigenvalue calculated in previous iteration

DEIG - Change in dominant eigenvalue in successive iterations

FCON - Convergence acceleration factor

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE EFLD2 USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

IVCK - Indicator which terminates the calculation of points on the voltage-current whenever the specified applied voltage is reached and interpolated upon

VO - Specified operating applied voltage (V)

VSTART - Particular value of VSTAR(I) [V]

VW - Operating applied voltage corresponding to a specified current density (V)

AC - Radius of the corona wires (m)

RO - Radius of the corona wires (m)

TDK - Temperature of the gas stream (°K)

P - Pressure of the gas stream (atm)

RELD - Relative air density [$\delta = (T_0/T)(P/P_0)$]

ROC - Radius of the corona wires (cm)

RF - Roughness factor for the corona wires

EORO - Product of the corona starting electric field and the wire radius (V)

I - Index which runs over grid points in the x-direction

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

J - Index which runs over grid points in the y-direction

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

UEQ - Effective charge carrier mobility (m^2/V-sec)

MOBILT(I,J) - Array containing the values of effective charge carrier mobility at the different grid points (m^2/V-sec)

PI - Value of the constant π

EPSO - Permittivity of free space ($coul^2/nt\text{-}m^2$)

START - Particular value of START1(I) [A/m^2]

SSTART - Initial value of START which is saved (A/m^2)

MINJ - Lower limit that the calculated average current density at the plate cannot fall below (A/m^2)

MAXS - Particular value of current density on the voltage-current curve (A/m^2)

NX1 - Number of grid intervals in the x-direction for the numerical calculations of electrical conditions

NY1 - Number of grid intervals in the y-direction for the numerical calculations of electrical conditions

SX - Wire-to-plate spacing in a particular linear electrical section (m)

AX - Interval size in the x-direction (m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section

AY - Interval size in the y-direction (m)

AXS - Value of the quantity $[a_x^2]$ (m^2)

AYS - Value of the quantity $[a_y^2]$ (m^2)

ASP - Value of the quantity $[(a_x^2+a_y^2)/\varepsilon_0]$ ($m^4\text{-}nt/coul^2$)

ASS - Value of the quantity $[1/2(a_x^2+a_y^2)]$(m^{-2})

IFINAL - Indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points

II - Index which runs over the different current densities to be used on the voltage-current curve

JI1 - Indicator which allows the initial increment size on current density in the calculation of the voltage-current curve to be changed after JI1-1 points are determined on the curve

DSTART - Particular value of START2(I) [A/m^2]

JI2 - Indicator which allows the second increment size on current density in the calculation of the voltage-current curve to be changed after JI2-1 points are determined on the curve

CSTART - Particular value of START3(I) [A/m^2]

MAXJ - Upper limit that the calculated average current density at the plate cannot exceed (A/m^2)

QZERO - Space charge density at the corona wire (coul/m^3)

NWIRE - Number of wires per electrical section per gas passage in a particular electrical section

Z - Counter which keeps track of the number of times the calculation iterates due to lack of convergence in the average current density at the plate

VCOOP(I,J) - Array containing the values of electric potential given equation (26) at the different grid points (V)

V(I,J) - Array containing the value of the electric potential at each point in the grid during an iteration (V)

IZ - Same as Z

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

LL - Counter which keeps track of the number of times the calculation iterates due to lack of convergence in the electric potential at each point in the grid

RHO(I,J) - Array containing the value of the space charge density at each point in the grid during an iteration (coul/m^3)

EX(I,J) - Array containing the value of the component of the electric field intensity perpendicular to the plates at each point in the grid during an iteration (V/m)

EY(I,J) - Array containing the value of the component of the electric field intensity parallel to the plates at each point in the grid during an iteration (V/m)

Q1 - Value of the quantity $[2b_{i,1}]$ along the line AD where $b_{i,j}$ is the effective charge carrier mobility which is a function of position (m^2/V-sec)

Q2 - Value of the quantity $[2b_{i,1}a_x]$ along the line AD (m^2/V-sec)

Q3 - Value of the quantity $[2b_{i,1}a_y]$ along the line AD (m^3/V-sec)

Q4 - Value of the quantity $[2b_{i,1}a_x a_y]$ along the line AD (m^4/V-sec)

Q5 - Value of the quantity $[-\varepsilon_0 E_x(2b_{i,1}a_y - a_y b_{i-1,1})]$ along the line AD (coul^2/nt-sec)

Q6 - Value of the quantity $[\varepsilon_0{}^2 E_x{}^2(2b_{i,1}a_y - a_y b_{i-1,1})^2]$ along the line AD (coul^4/nt^2-sec^2)

Q7 - Value of the quantity $[4b_{i,1}^2 a_x a_y{}^2 \varepsilon_0 E_x \rho_{i-1,1}]$ along the line AD where $\rho_{i,j}$ is the space charge density at the different grid points (coul^2-m^2/V^2-sec^2)

Q8 - Value of the quantity $[-\sqrt{Q6+Q7}]$ along the line AD (coul-m/V-sec)

P1 - Value of the quantity $[2b_{1,j}]$ along the line AB (m^2/V-sec)

P2 - Value of the quantity $[2b_{1,j}a_x]$ along the line AB (m^3/V-sec)

P3 - Value of the quantity $[2b_{1,j}a_y]$ along the line AB (m^3/V-sec)

P4 - Value of the quantity $[2b_{1,j}a_x a_y]$ along the line AB (m^4/V-sec)

P5 - Value of the quantity $[-\varepsilon_0 E_y(2b_{1,j}a_x - a_x b_{1,j-1})]$ along the line AB (coul^2/nt-sec)

P6 - Value of the quantity $[\varepsilon_0{}^2 E_y{}^2(2b_{1,j}a_x - a_x b_{1,j-1})^2]$ along the line AB (coul^4/nt^2-sec^2)

P7 - Value of the quantity $[4b^2_{1,j}a_x{}^2 a_y \varepsilon_0 E_y \rho_{1,j-1}]$ along the line AB (coul^2-m^2/V^2-sec^2)

P8 - Value of the quantity $[-\sqrt{P6+P7}]$ along the line AB (coul-m/V-sec)

R1 - Value of the quantity $[2b_{i,NY}]$ along the line BC (m^2/V-sec)

R2 - Value of the quantity $[2b_{i,NY}a_x]$ along the line BC (m^3/V-sec)

R3 - Value of the quantity $[2b_{i,NY}a_y]$ along the line BC (m^3/V-sec)

R4 - Value of the quantity $[2b_{i,NY}a_x a_y]$ along the line BC (m^4/V-sec)

R5 - Value of the quantity $[-\varepsilon_0 E_x(2b_{i,NY}a_y - a_y b_{i-1,NY}]$ along the line BC ($coul^2$/nt-sec)

R6 - Value of the quantity $[\varepsilon_0{}^2 E_x^2(2b_{i,NY}a_y - a_y b_{i-1,NY}]$ along the line BC ($coul^4/nt^2-sec^2$)

R7 - Value of the quantity $[4b_{i,NY}^2 a_x a_y^2 \varepsilon_0 E_x \rho_{i-1,NY}]$ along the line BC ($coul^2-m^2/V^2-sec^2$)

R8 - Value of the quantity $[-\sqrt{R6+R7}]$ along the line BC (coul-m/V-sec)

D1 - Value of the quantity $[2b_{i,j}]$ for interior points in the grid (m^2/V-sec)

D2 - Value of the quantity $[2a_x b_{i,j}]$ for interior points in the grid (m^3/V-sec)

D3 - Value of the quantity $[2a_y b_{i,j}]$ for interior points in the grid (m^3/V-sec)

D4 - Value of the quantity $[2a_x a_y b_{i,j}]$ for interior points in the grid (m^4/V-sec)

D5 - Value of the quantity $[-\varepsilon_0(E_x(2a_y b_{i,j} - a_y b_{i-1,j}) + E_y(2a_x b_{i,j} - a_x b_{i,j-1}))]$ for interior points in the grid ($coul^2$/nt-sec)

D6 - Value of the quantity $[D5 \cdot D5]$ ($coul^4/nt^2-sec^2$)

D7 - Value of the quantity $[4b_{i,j}^2 a_x a_y \varepsilon_0(a_y E_x \rho_{i-1,j} + a_x E_y \rho_{i,j-1})]$ for interior points in the grid ($coul^2-m^2/V^2-sec^2$)

D8 - Value of the quantity $[-\sqrt{D6+D7}]$ for interior points in the grid (coul-m/V-sec)

OLDV(I,J) - Array containing the value of the electric potential at each point in the grid during the previous iteration (V)

OLDRO(I,J) - Array containing the value of the space charge density at each point in the grid during the previous iteration (coul/m^3)

CDNSTY(I,J) - Array containing the value of current density at each point in the grid (A/m^2)

ACDNTY - Average current density at the plate (A/m^2)

TEST - Absolute value of the difference between the calculated average current density at the plate and the specified value (A/m^2)

TEST1 - One percent of the calculated average current density at the plate (A/m^2)

EPLT - Sum of the values of the electric field intensity at the plate (V/m)

AEPLT - Average electric field at the plate (V/m)

EBD - Electrical breakdown strength of the gas near the collection electrode or the collected particulate layer (V/m)

OLDVW - The value of applied voltage at the point prior to the one under consideration (V)

OLDCD - The value of average current density at the plate at the point prior to the one under consideration (A/m^2)

NEC - Indicator which determines whether or not the average current density, average electric field, and average electric field at the plate are to be calculated in the subincremental lengths

K - Index which sequences the grid strips in the basic area for which the calculations are performed

RSUM - Average charge number density in a particular grid strip (#/m^3)

ESUM - Average electric field intensity in a particular grid strip (V/m)

EAVGS(K) - Array containing the average electric field intensities in the different grid strips in the basic area for which the calculations are performed (V/m)

CHFIDS(K) - Array containing the average charge number densities in the different grid strips in the basic area for which the calculations are performed (#/m^3)

NYY - Index which renumbers the grid strips so that by symmetry the area covered by the half-wire spacing which was not considered in the calculations can be taken into account

EAVG(L) - Array containing the average electric field intensities in the different grid strips which cover an area between successive wires (V/m)

CHFID(L) - Array containing the average charge number densities in the different grid strips which cover an area between successive wires (#/m^3)

L - Index which runs over and numbers the first (NY-1) grid strips in a given wire-to-wire spacing

KK - Index which runs over the different grid strips in the basic area for which the calculations are performed

M1 - Number of the first grid strip in the last (NY-1) grid strips in a given wire-to-wire spacing

M2 - Number of the last grid strip in a given wire-to-wire spacing

M - Index which runs over and numbers the last (NY-1) grid strips in a given wire-to-wire spacing

LL - Index which sequences the grid strips in the basic area for which the calculations are performed

NN - Index which runs over points in the y-direction

ECOLLS(LL) - Array containing the average electric field intensity at the plate in the different grid strips in the basic area for which the calculations are performed (V/m)

L1 - Index which renumbers the grid strips so that by symmetry the area covered by the half-wire spacing which was not considered in the calculations can be taken into account

ECOLL(L) - Array containing the average electric field intensity at the plate in the different grid strips which cover an area between successive wires (V/m)

L2 - Index which runs over the different grid strips in the basic area for which the calculations are performed

I1 - Number of the first grid strip in the last (NY-1) grid strips in a given wire-to-wire spacing

I2 - Number of the last grid strip in a given wire-to-wire spacing

I - Index which runs over and numbers the last (NY-1) grid strips in a given wire-to-wire spacing

CON - Factor used to adjust potential across grid

VSTR(I,J,NSCT) - Storage register for V(I,J) from each increment

ANX - Exponent for adjusting applied voltage using power law correlation with current density

ITER - Number of times calculation iterates without converging since last acceleration step

DV - Difference in potential from preceding to current iteration at each grid point

DVR - Normalized change in potential at each grid point

DVRM - Maximum normalized change in potential at each grid point

DXM - Norm of potential differences across grid used for calculating dominant eigenvalue

DXML - Value of DXM from preceding iteration

EIG1 - Dominant eigenvalue

EIGL - Dominant eigenvalue calculated in previous iteration

DEIG - Change in dominant eigenvalue in successive iterations

ECONV - Potential convergence criterion

ECONI - Convergence criterion on eigenvalue before acceleration step can be performed

IJMIN - Number of times the calculation iterates without converging before new acceleration step performed

ITMAX - Maximum number of iterations allowed for convergence of potential across grid

IZMAX - Maximum number of iterations allowed for convergence on current density

ALPH - Damping factor included in dominant eigenvalue calculation to prevent instability

FCON - Convergence acceleration factor

VWOLD - Value of wire voltage taken before the voltage is adjusted and used to define CON

VWX - Value of wire voltage in previous increment used to define CON in current increment

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE CHARGN USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

H - Increment size used in the Runge-Kutta scheme (sec)

YI - Time at the start of a given increment or subincrement of the precipitator (sec)

Y - Time at the end of a given increment or subincrement of the precipitator (sec)

I - Index which runs over the different points specified for use in the Runge-Kutta scheme

NN - Number of points specified for use in the Runge-Kutta scheme

SCHARG - Saturation charge number from the field charging equation

DCONST - Value of the quantity $[(K-1)a^3/(K+2)]$ found in equation (12) $[m^2]$

EZERO - Average electric field used for particle charging (V/m)

V - Value of the quantity $[e^2/4\pi\varepsilon_0 akT]$ found in equation (12)

RSIZE - Radius of a particular particle (m)

ECONST - Value of the quantity $[3eE_0 a/kt(K+2)]$ found in equation (12)

RR - Value of the quantity $[eE_0/kT]$ found in equation (12) $[m^{-1}]$

FACTOR - Value of the quantity $[\pi\tilde{v}a^2/2]$ found in equation (12) $[m^3/sec]$

COEFF - Value of the quantity $[bq_s/4\varepsilon_0]$ found in equation (12) $[m^3/sec]$

AFID - Average reduced free ion density for particle charging in a particular length increment $(\#/m^3)$

T1 - Value of the charge-number rate to the particle surface at the point (XI,YI) multiplied by the stepsize H for use in the Runge-Kutta scheme

T2 - Value of the charge-number rate to the particle surface at the point (XI+H2, YI+T1/2) multiplied by the stepsize H for use in the Runge-Kutta scheme

T3 - Value of the charge-number rate to the particle surface at the point (XI+H2, YI+T2/2) multiplied by the stepsize H for use in the Runge-Kutta scheme

T4 - Value of the charge-number rate to the particle surface at the point (XI+H, YI+T3) multiplied by the stepsize H for use in the Runge-Kutta scheme

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR FUNCTION SUBPROGRAM RATE USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

ECHARG - Elementary charge unit (coul)

SCHARG - Saturation charge number from the field charging equation

DCONST - Value of quantity $[(K-1)a^3/(K+2)]$ found in equation (12) $[m^2]$

EZERO - Average electric field used for particle charging (V/m)

V - Value of the quantity $[e^2/4\pi\varepsilon_0 akT]$ found in equation (12)

RSIZE - Radius of a particular particle (m)

ECONST - Value of the quantity $[3eE_0 a/kT(K+2)]$ found in equation (12) $[V\text{-}m^2]$

CMKS - Value of the quantity $[4\pi\varepsilon_0]$ found in equation (12) $[\text{coul}^2/\text{nt-m}^2]$

RR - Value of the quantity $[eE_0/kT]$ found in equation (12) $[m^{-1}]$

FACTOR - Value of the quantity $[\pi\tilde{v}a^2/2]$ found in equation (12) $[m^3/\text{sec}]$

COEFF - Value of the quantity $[bq_s/4\varepsilon_0]$ found in equation (12) $[m^3/\text{sec}]$

AFID - Average reduced free ion density for particle charging in a particular length increment $(\#/m^3)$

NUMBER - Instantaneous number of charges on a given particle size

T(I) - Roots of the Legendre polynomials of third order

WGAUS(I) - Gaussian weighting functions

THZERO - Maximum angle (θ_0) for field charging in radians

YFUC - The quadrature being computed

THETA - Values of the angle θ taken for the integration over θ in equation (12)

CTHETA - Value of the quantity [cos θ]

STHETA - Value of the quantity [sin θ]

CP - Value of the quantity [$q/4\pi\varepsilon_0 E_0$]

C0 - Value of the quantity [$(K-1)a^3/(K+2)$]

C1 - Value of the quantity [CP/cos θ]

RZERO - Radial distance from the center of a given particle at which the total radial component of the electric field is zero (m)

ARG1 - Argument of the exponential function inside the integral in equation (12)

YVAL - Integrand of the integral in equation (12)

RATE2 - Contribution to the particle charging rate due to the second term in equation (12) [#/sec]

ARG3 - Argument of the exponential function in the third term in equation (12)

RATE3 - Contribution to the particle charging rate due to the third term in equation (12)

RATE1 - Contribution to the particle charging rate due to the first term in equation (12) [#/sec]

RATE - Total instantaneous charging rate to the entire surface of a given particle (#/sec)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE ARCCOS USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

A - Numerator of the ratio A/B whose inverse cosine is to be determined

B - Denominator of the ratio A/B whose inverse cosine is to be determined

RCOS - Value of the quantity $[\cos^{-1}(A/B)]$ (radians)

RATIO - Value of the ratio A/B

T - Variable used to generate the different numerical coefficients in the series representation of the inverse cosine function

SUM - Sum of successive terms in the series representation of the inverse cosine function

TERM - A particular term in the series representation of the inverse cosine function

U - Variable used in the generation of the numerical coefficients in the series representation of the inverse cosine function

V - Variable used in the generation of the numerical coefficients in the series representation of the inverse cosine function

W - Variable used in the generation of the numerical coefficients in the series representation of the inverse cosine function

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE ZERO USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

C1 - Value of the quantity $[q/4\pi\varepsilon_0 E_0 \cos\theta]$ found in equation (52)

C0 - Value of the quantity $[(K-1)a^3/(K+2)]$ found in equation (52) $[m^3]$

RZERO - Radial distance from the center of a given particle at which the total radial component of the electric field is zero (m)

B - Value of the argument of the inverse cosine function found in equation (55)

C - Value of the inverse cosine function found in equation (55)

D - Factor multiplying the cosine function found in equation (12)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE CHGSUM USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

I - Index which runs over incremental lengths

II - Index which runs over subincremental lengths

OLDQF(J) - Value of field charge on the different particle sizes at the end of a given increment or subincrement (coul)

OLDQT(J) - Value of diffusion charge on the different particle sizes at the end of a given increment or subincrement (coul)

ITER - Counter which keeps track of the number of iterations which is limited by NITER

SOLDQF(J) - Value of field charge on the different particle sizes at the start of an increment which must be saved for the iteration procedure over subincrements in a given increment (coul)

SOLDQT(J) - Value of diffusion charge on the different particle sizes at the start of an increment which must be saved for the iteration procedure over subincrements in a given increment (coul)

E - Elementary charge unit (coul)

SCHARG - Saturation charge number from the field charging equation

SATCHG - Saturation charge for a given particle size from field charging theory (coul)

CHRFID - Average free ion density for particle charging $(\#/m^3)$

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

EPSO - Permittivity of free space ($coul^2/nt\text{-}m^2$)

TIMEF - Final value of time for particle charging (sec)

TIMEI - Initial value of time for particle charging (sec)

CF1 - Value of the quantity $[(N_0 be/4\varepsilon_0)(t_f - t_i)]$ found in equation (15)

CF2 - Value of the quantity $[1/(1 - q_i/q_s)]$ found in equation (15)

QF - Charge on a given particle size in a given increment or subincrement due to field charging (coul)

V - Value of the quantity $[e^2/4\pi\varepsilon_0 akT]$ found in equation (15)

ARG - Value of the quantity $[q_i e/4\pi\varepsilon_0 akT]$ found in equation (15)

RSIZE - Radius of a particular particle (m)

VAVC - Root mean square velocity of the ions (m/sec)

BC - Boltzmann's constant (J/°K)

TDK - Temperature of the gas in a given electrical section (°K)

QT - Charge on a given particle size in a given increment or subincrement due to diffusion charging (coul)

CNUMBR - Total charge number on a given particle size in a given increment or subincrement

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE PRTINC USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NPRINT - Indicator which designates when to print certain sectionalized data

NSECT - Indicator which keeps track of which electrical section the calculation is in

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

ITL - Identifying label for the calculations

SLNGTH - Length of a particular electrical section (m)

A - Collection plate area of a particular linear electrical section (m^2)

VO - Applied voltage in a particular linear electrical section (V)

TC - Total current in a particular linear electrical section (A)

B - Wire-to-plate spacing in a particular linear electrical section (m)

AC - Corona wire radius in a particular linear electrical section (m)

WL - Total wire length in a particular linear electrical section (m)

CL - Total current per length of corona wire in a particular linear electrical section (A/m)

CD - Average current density at the plate in a particular linear electrical section (A/m^2)

ET - Average electric field in the deposited particulate layer in a particular linear electrical section (V/m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section (m)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

VGAS - Gas velocity in a particular linear electrical section (m/sec)

TDK - Temperature of the gas in a given electrical section (°K)

P - Gas pressure in a particular linear electrical section (atm)

VIS - Gas viscosity in a particular linear electrical section (kg/m-sec)

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

VAVC - Root mean square velocity of the ions (m/sec)

TMFP - Ionic mean free path multiplied by a factor (m)

W - Total weight of particles per second passing into a particular linear electrical section (kg/sec)

LINC - Length of the increments taken in a particular linear electrical section (m)

XPI - Overall mass collection efficiency per increment based on the estimated or design efficiency (%)

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

RIOVR - Ratio of the ionic space charge density to the total space charge density

ERAVG - Average electric field used for particle charging (V/m)

EPLT - Absolute value of the average electric field at the plate in a particular length increment (V/m)

AFID - Average reduced free ion density for particle charging in a particular length increment (#/m^3)

XCD - Average current density at the plate in a particular length increment (nA/cm^2)

ZMD - Interpolated mass median diameter of the collected particulate layer (m)

WT - Total weight of material per cubic meter of gas removed in all particle size bands in a given length increment (kg/m^3)

LTHICK - Thickness of the collected particulate layer in a particular increment of length (mm/min)

JPART - Current density due to particles in a particular increment of length (A/m^2)

JION - Current density due to ions in a particular increment of length (A/m^2)

I - Index which runs over incremental lengths

ROVRI - Ratio of the total space charge density to the ionic space charge density

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE PRTCHG USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

NCALC - Indicator which determines whether to use equation (12) for particle charging or the sum of the classical field and diffusion charges

NEST - Indicator which specifies whether to use extensive calculations or estimation procedures in determining precipitator performance

JS - Index which is utilized in dividing the output data for particle charging into sets of eight columns each with a column for each particle size band

KS - Index which is utilized in dividing the output data for particle charging into sets of eight columns each with a column for each particle size band

NS - Number of different particle size bands in the inlet particle size distribution

DIAM(J) - Diameters of the different particle sizes (μm and m)

J - Index which runs over the different particle size bands

I - Index which runs over incremental lengths

NF - Number of increments taken along the length of the precipitator

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

NI - Number of subincremental lengths into which the incremental length is divided

N - Number of the subincremental strip having the maximum values of average electric field and current density

PI - Value of the constant π

EPSO - Permittivity of free space ($coul^2/nt\text{-}m^2$)

RAD(J) - Radii of the different particle sizes (m)

TMFP - Ionic mean free path multiplied by a factor (m)

EAVG(N) - Average electric fields for particle charging in subincremental lengths (V/m)

EPS - Relative dielectric constant of the particles

VRATIO - Ratio of the peak applied voltage to the average for use in particle charging

XDC(I,J) - Charge on each particle size at the end of each increment (coul)

QSATM - Saturation charge for a given particle size based on the last electrical section and the subincremental strip containing the largest values of average electric field and current density (coul)

YY(J) - Array containing the ratio of the charge on a given particle size to the saturation charge in the last electrical section for a given increment

QSAT(J) - Saturation charge for a given particle size based on the last electrical section and the average electric field for the entire section (coul)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE WADJST USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

DIAM(I) - Diameters of the different particle sizes (μm and m)

I - Index which runs over the different particle size bands

WY - Enters the subroutine as the unadjusted, no-rap migration velocity for a given particle size and leaves as the adjusted, no-rap migration velocity (cm/sec)

ONO(I) - Initial number of particles per cubic meter of gas in each particle size band (#/m^3)

PXS(I) - Number of particles per cubic meter of gas for a given particle size that are removed by the precipitator under adjusted, no-rap conditions (#/m^3)

ATOTAL - Total collection plate area of the precipitator (m^2)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

EFESR - Mass collection fraction for a given particle size under adjusted, no-rap conditions

CFACT(L) - Correction factors for the no-rap migration velocities of the different particle sizes

DCHECK(L) - Particle diameters corresponding to the different correction factors given by CFACT(L) [m]

L - Index which runs over the different values of CFACT(L) and DCHECK(L)

WFACT - Interpolated correction factor for the unadjusted, no-rap migration velocity of a given particle size

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE LNDIST USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

D50 - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMAP - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

PRCU(I) - Cumulative fractions by mass up to specified particle sizes

PCNT(J) - Fractions by mass contained in specified particle size bands

Y(K) - Values of the log-normal distribution function at different values of the independent variable for use in integrating the function over the specified size bands

Z(K) - Cumulative integrals resulting from the integration of the log-normal distribution function over a specified particle size band

AREA(J) - Amount of the distribution accumulated in a given particle size band

NS - Number of particle size bands

ENDPT(I) - Particle diameters specified for use in constructing the log-normal distribution histogram (μm)

NENDPT - Number of particle diameters specified for use in constructing the log-normal distribution histogram

PI - Value of the constant π

SIGMAZ - Value of the quantity [ln σ_ρ]

N - Total number of particle size bands used in constructing the log normal distribution histogram

NINC - Number of points used in the Trapezoidal Rule integrations over the different particle size bands

ASUM - Value of the integration of the log-normal distribution function over the entire distribution

K - Index which runs over the NS different particle size bands specified by the user

J - Index which runs over the N different particle size bands used in the construction of the log-normal distribution histogram

X2 - Upper limit of integration for a given particle size band

X1 - Lower limit of integration for a given particle size band

DX - Stepsize taken for the Trapezoidal Rule integration of the log-normal distribution function over the different particle size bands

D - Value of the integration variable at different points in a given particle size band

SGT1 - Value of the quantity $[1/\sigma_z\sqrt{2\pi}]$

SGT2 - Value of the quantity $[2\sigma_z^2]$

I - Index which runs over the different points in a given particle size band in performing the Trapezodial Rule integration of the log-normal distribution function

SUM - Total fraction by mass contained in the histogram specified by the user

CHECK1 - Difference between 1 and the calculated total mass fraction contained in the histogram specified by the user

CHECK2 - Difference between 1 and the calculated cumulative fraction by mass up to the largest particle size specified by the user

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE QTFE USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

DX - Stepsize used in the Trapezoidal Rule integration scheme

Y(I) - Function values used in the integration scheme

Z(I) - Cumulative integrals resulting from the integration scheme

NINC - Number of points used in the integration scheme

SUM2 - Cumulative integral up to a given point in the integration scheme

DDX - One-half of the specified stepsize

I - Index which runs over the different points in the integration scheme

SUM1 - Cumulative integral up to the point prior to the point under consideration

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE LNFIT USED IN THE ELECTRISTATIC PRECIPITATOR PERFORMANCE MODEL

PRCU(I) - Known or calculated cumulative percentages supplied by the user (%)

D50 - Fitted mass median diameter based on a log-normal distribution (μm)

SIGMAP - Fitted geometric standard deviation based on a log-normal distribution

GFIT - Linear-correlation coefficient obtained in the log-normal fit

Z(I) - Natural logarithm of the actual particle diameters corresponding to the known or calculated cumulative percentages

Y(I) - Calculated natural logarithm of the particle diameters corresponding to the known or calculated cumulative percentages based on a true log-normal distribution

ENDPT(I) - Actual particle diameters corresponding to the known or calculated cumulative percentages (μm)

NENDPT - Number of particle diameters corresponding to the known or calculated cumulative percentages

NSTAG - Number of points used in the log-normal fit procedure

I - Index which runs over the different particle diameters corresponding to the known or calculated cumulative percentages

J - Index which sequences the points which are actually used in the log-normal fit

XY - Cumulative mass fraction less than a given particle size

XYY - Square root of the natural logarithm of the square of the reciprocal of XY

A - Y-intercept of the fitted straight line

B - Slope of the fitted straight line

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE CFIT USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

A - Y-intercept of the fitted straight line

B - Slope of the fitted straight line

R - Linear-correlation coefficient for the straight line fit

NSTAG - Number of data points that are fitted to the straight line

Z(I) - Values of the independent variable

Y(I) - Values of the dependent variable

XN - Running sum over the number of data points

SUMX - Summation over all data points of the values of the independent variable

SUMY - Summation over all data points of the values of the dependent variable

SUMXY - Summation over all data points of the values of the product of the independent and dependent variables

SUMXX - Summation over all data points of the values of the square of the independent variable

SUMYY - Summation over all data points of the values of the square of the dependent variables

I - Index which runs over the different data points

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE PRTSUM USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

ATOTAL - Total collection plate area of the precipitator (m^2)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

SCA - Specific collection area of the precipitator (m^2/m^3/sec)

VOSUM - Sum of the applied voltages in the different linear electrical sections (V)

CDSUM - Sum of the current densities in the different linear electrical sections (nA/cm^2)

NUMSEC - Number of linear electrical sections in the precipitator

LSECT(I) - Number of length increments in the different linear electrical sections

LINCS(I) - Lengths of the increments taken in the different linear electrical sections (ft)

I - Index which runs over the different linear electrical sections

VOS(I) - Applied voltages for the different linear electrical sections (V)

TCS(I) - Total current for the different linear electrical sections (A)

AS(I) - Collection plate areas for the different linear electrical sections (m^2)

AVO - Average applied voltage over the entire precipitator (V)

PL - Total electrical length of the precipitator (ft and m)

ACD - Average current density over the entire precipitator (nA/cm^2)

RHO - Resistivity of the collected particulate layer (ohm-m)

RHOCGS - Resistivity of the collected particulate layer (ohm-cm)

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

NRUN - Indicator that specifies which set of nonideal conditions is under consideration

SCOREF - Overall mass collection efficiency under no-rap + rap conditions (%)

ZMMDI - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMI - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

CZMDL - Fitted log-normal mass median diameter of the outlet particle size distribution under no-rap + rap conditions (μm)

CSIGMO - Fitted log-normal geometric standard deviation of the outlet particle size distribution under no-rap + rap conditions

SNUCK - Particular value of ASNUCK(JJ)

ZIGGY - Particular value of AZIGGY(JJ)

RMMD - Particular value of ARD50(II) [μm]

RSIGMA - Particular value of ARSIGM(II)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE CMAN USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

NX1 - Number of grid intervals in the x-direction for the numerical calculations of electrical conditions

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

NY1 - Number of grid intervals in the y-direction for the numerical calculations of electrical conditions

SX - Wire-to-plate spacing in a particular linear electrical section (m)

AX - Interval size in the x-direction (m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section (m)

AY - Interval size in the y-direction (m)

I - Index which runs over grid points in the x-direction

J - Index which runs over grid points in the y-direction

X - Value of x used in equation (26) [m]

Y - Value of y used in equation (26) [m]

VW - Electrical potential at the wire (V)

VCOOP(I,J) - Array containing the values of electric potential given equation (26) at the different grid points (V)

NWIRE - Number of wires per electrical section per gas passage in a particular electrical section

M - Series sum in equation (26) is taken from -M to M

NUM - Sum in the numerator of equation (26)

DENOM - Sum in the denominator of equation (26)

PI - Value of the constant π

E1 - Arguments for the hyperbolic cosine functions in the numerator of equation (26)

F1 - Arguments for the cosine functions in the numerator of equation (26)

G1 - Arguments for the hyperbolic cosine functions in the denominator of equation (26)

H1 - Arguments for the cosine functions in the denominator of equation (26)

E2 - Hyperbolic cosine functions in the denominator of equation (26)

F2 - Cosine functions in the denominator of equation (26)

G2 - Hyperbolic cosine functions in the denominator of equation (26)

H2 - Cosine functions in the denominator of equation (26)

TT - Argument for the logarithmic function in the numerator of equation (26)

TB - Argument for the logarithmic function in the denominator of equation (26)

F - Logarithmic function in the numerator of equation (26)

G - Logarithmic function in the denominator of equation (26)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE MIE USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

C1 - Real part of complex index of refraction

C4 - Imaginary part of complex index of refraction

X - Size parameter = π*DIAMETER/WAVELENGTH

A1 - Angle of scattering

E1 - Scattering intensity perpendicular to scattering plane

E2 - Scattering intensity parallel to scattering plane

R1 - Scattering efficiency

R2 - Absorption efficiency

R3 - Extinction efficiency

S1 - Real part of the scattering amplitude perpendicular to the scattering plane

S2 - Real part of the scattering amplitude parallel to the scattering plane

S3 - Imaginary part of the scattering amplitude perpendicular to the scattering plane

S4 - Imaginary part of the scattering amplitude parallel to the scattering plane

C2 - Cosine of the scattering angle

S - Sine squared of the scattering angle

T - Deirmendjian test value = 1.2 * X + 9

X1 - Parameter used to simplify coding the mathematical expressions = C1 * X

X2 - Parameter used to simplify coding the mathematical expressions = C4 * X

C - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

C3 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

Z2 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

Z3 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

Z4 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

Z5 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

Z6 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

Z7 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

A - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

A7 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

Y - Sine of the size parameter

Z - Cosine of the size parameter

W4 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

W5 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

W2 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

W3 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

P1 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

P - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

T2 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

T1 - Term used to simplify coding in the calculation of Mie coefficients a_n and b_n

R4 - Summation index for calculation of extinction and scattering efficiencies

A4 - Mathematical expression used in the calculation of Mie coefficient a_n

A5 - Mathematical expression used in the calculation of Mie coefficient a_n

A6 - Mathematical expression used in the calculation of Mie coefficient a_n

A8 - Mathematical expression used in the calculation of Mie coefficient a_n

A2 - Real part of Mie coefficient a_n

A3 - Imaginary part of Mie coefficient a_n

B4 - Mathematical expression used in the calculation of Mie coefficient b_n

B5 - Mathematical expression used in the calculation of Mie coefficient b_n

B6 - Mathematical expression used in the calculation of Mie coefficient b_n

B8 - Mathematical expression used in the calculation of Mie coefficient b_n

B2 - Real part of Mie coefficient b_n

B3 - Imaginary part of Mie coefficient b_n

R5 - Coefficient = $2n + 1$ or $2/X^2$

R6 - Coefficient = $(2n + 1)/n(n + 1)$

B - Value of $|a_n|^2 + |b_n|^2$ used to calculate the scattering efficiency

P2 - Term used in calculation of Mie coefficients a_n and b_n

T3 - Term used in calculation of Mie coefficients a_n and b_n

W6 - Term used in calculation of Mie coefficients a_n and b_n

W7 - Term used in calculation of Mie coefficients a_n and b_n

C5 - Term used in calculation of Mie coefficients a_n and b_n

C6 - Term used in calculation of Mie coefficients a_n and b_n

D1 - Deirmendjian test value = 1.0E-14

R2 - Absorption efficiency

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE ARAOPT USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NODES - Number of size bands

D - Particle diameter (μm)

FD - Normalized differential area distribution

TOTARA - Total projected area of the effluent particles (m^2/ACM)

TTOPAR - Total extinction coefficient (m^{-1})

OFD - Differential extinction coefficient distribution (m^{-1})

LAMDA - Wavelengths at which extinction efficiency is calculated (μm)

FLAMDA - Normalized photopic response of the human eye at each wavelength LAMDA

DELMDA - Difference between each calculation wavelength LAMDA

ANG - Angle at which extinction efficiency is calculated (= 0 for opacity measurements)

NWAVES - Number of calculation wavelengths to be used in calculation (= 1 or 10)

NRMCST - Normalized extinction efficiency

QBR - Extinction efficiency in each particle size band adjusted for photopic response

JJ - A counter

JJJ - A counter

ALPHA - Particle size parameter = π*Diameter/Wavelength

JLMDAC - A counter

JC - A counter

UPTOLM - Maximum wavelength in each wavelength band used with variable composition calculation

NCOMP - Composition counter with maximum value NCOMPS

NTIMES - Indicator used to avoid repeating many calculations

NNCOMP - Indicator used to avoid repeating many calculations

CMR - Real part of index of refraction

CMI - Imaginary part of index of refraction

AIL - Scattering intensity perpendicular to the scattering plane

EIR - Scattering intensity parallel to the scattering plane

QS - Scattering efficiency

QA - Absorption efficiency

Q - Extinction efficiency

QARRAY - Extinction efficiency from previous calculations

DELTAD - Value of $\Delta\log_{10}$ (Diameter) in each size band

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE MASARA USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

DENSTY - Particle density (g/cm^3)

NOXES - Number of particle size bands

X - Particle diameter (μm)

FX - Differential mass distribution (g/ACM) and normalized differential projected area distribution

DELTAX - Value of $\Delta \log_{10}$ (Diameter) for each particle size band

TOTMAS - Total mass leaving the precipitator (g/ACM)

TOTARA - Total projected area of the particles leaving the precipitator (m^2/ACM)

NRMCST - Normalization constant for the area distribution (g/ACM/μm or μm^{-1})

NRMCSM - Summation of differential mass times $\Delta \log D$ used to determine whether the differential mass distribution is normalized (g/ACM or unitless)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE ADJUST USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NRUN - Indicator that specifies which set of nonideal conditions is under consideration

NS - Number of different particle size bands in the inlet particle size distribution

NS1 - Number of particle size bands plus one

NUMSEC - Number of linear electrical sections in the precipitator

NUMS1 - Number of electrical sections less one

TDK - Temperature of the gas stream in the last electrical section (°K)

PS(NUMSEC) - Pressure of the gas stream in the last electrical section (atm)

CONVF - Conversion factor which converts kg/ACM to mg/DSCM

NRAPDC - Counter which keeps track of the number of rapping puff particle size distributions that have been considered

X - Ideal, unadjusted overall mass collection fraction (or efficiency) [no units or %]

I - Index which runs over the different particle size bands

DXS(I) - Total number of particles removed per cubic meter of gas in each particle size band under ideal conditions and with no empirical corrections (#/m^3)

ONO(I) - Initial number of particles per cubic meter of gas in each particle size band (#/m^3)

EFESR - Ideal, unadjusted mass collection fraction for a given particle size

PCNT(I) - Percentage or fraction by mass in the inlet particle size distribution of the different size bands (% and decimal)

ARD50(J) - Rapping puff mass median diameters (μm)

ARSIGM(J) - Rapping puff geometric standard deviations

RMMD - Particular value of ARD50(J)[μm]

RSIGMA - Particular value of ARSIGM(J)

RPRCU(I) - Cumulative fraction by mass as a function of particle size for the rapping puff

RPCNT(I) - Percentages by mass in the different particle size bands for the rapping puff (%)

NONCK - Counter which keeps track of the number of sets of nonideal conditions of nonuniform velocity distribution and gas sneakage and/or particle reentrainment without rapping that have been considered

ASNUCK(K) - Fractions of gas sneakage and/or particle reentrainment without rapping

SNUCK - Particular value of ASNUCK(K)

AZIGGY(K) - Normalized standard deviations of the gas velocity distribution

ZIGGY - Particular value of AZIGGY(K)

AZNUMS(K) - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur

ZNUMS - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur for a particular case

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

Y - Adjusted overall mass collection fraction (or efficiency) under no-rap conditions (no units or %)

XEP - Adjusted mass collection fraction for a given particle size band under no-rap conditions

XMV(I) - Effective migration velocities for the different particle sizes under ideal conditions and with no empirical corrections (m/sec)

WY - Adjusted migration velocity for a given particle size under no-rap conditions (cm/sec)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

ATOTAL - Total collection plate area of the precipitator (m^2)

F1 - Correction factor for the migration velocity of a given particle size in order to account for nonuniform velocity distribution

F2 - Correction factor for the migration velocity of a given particle size in order to account for gas sneakage and/or particle reentrainment without rapping

WYS - Migration velocity of a given particle size corrected only for gas sneakage and/or particle reentrainment without rapping (cm/sec)

WYV - Migration velocity of a given particle size corrected only for nonuniform velocity distribution (cm/sec)

ZNLFF - Combined correction factor for nonuniform velocity distribution and gas sneakage and/or particle reentrainment without rapping

WYSV - Migration velocity of a given particle size corrected only for nonuniform gas velocity distribution and gas sneakage and/or particle reentrainment without rapping (cm/sec)

WUNCOR(I) - Unadjusted, ideal migration velocities for the different particle sizes (cm/sec)

EUNCOR(I) - Unadjusted, ideal mass collection efficiencies for the different particle sizes (%)

DIAM(I) - Diameters of the different particle sizes (μm and m)

PXS(I) - Number of particles per cubic meter of gas for a given particle size that are removed by the precipitator under adjusted, no-rap conditions (#/m^3)

IDC - Indicator which controls when the summation of outlet emissions over the different particle size bands will be performed

SPO - Total outlet emissions under adjusted, no-rap conditions ($\#/m^3$)

SCPO - Total outlet emissions under rap + no-rap conditions ($\#/m^3$)

IX - Indicator which determines when the total electrical length up to the last electrical section will be calculated

SCOREF - Overall mass collection efficiency under no-rap + rap conditions (%)

XY - Percentage by mass in a given particle size in the inlet particle size distribution (%)

PENTR - Percentage by mass of a given particle size that penetrates through the precipitator under adjusted, no-rap conditions (%)

PCTOT(I) - Percentage by mass in a given particle size band in the no-rap outlet emissions (%)

CLPTLS - Total electrical length of the precipitator excluding the last electrical section (m)

IS - Index which runs over the different linear electrical sections

LSECT(IS) - Number of length increments in the different linear electrical sections

LINCS(IS) - Lengths of the increments taken in the different linear electrical sections (ft)

NYX - Index which starts and terminates a loop in which the mass loss due to rapping and the mass leaving the precipitator under no-rap conditions are determined

XEFF - Overall mass collection fraction for either unadjusted, ideal or adjusted, no-rap conditions

NEFF - Indicator which determines whether the unadjusted, ideal or adjusted, no-rap efficiency is used to determine the mass reentrained due to rapping

EXPONT - Argument of the exponential function in equation (2) for either the unadjusted, ideal efficiency or the adjusted, no-rap efficiency

DL - Inlet mass loading (kg/m^3)

PL - Total electrical length of the precipitator (m)

XMELS - Mass entering the last section of the precipitator from either unadjusted, ideal or adjusted, no-rap calculations (kg/m^3)

XMCLS - Mass collected in the last section of the precipitator from either unadjusted, ideal or adjusted, no-rap calculations (kg/m^3 or mg/DSCM)

XMLLS - Mass leaving the last section of the precipitator from either unadjusted, ideal, or adjusted, no-rap calculations (kg/m^3)

NTEMP - Indicator which specifies whether the precipitator is cold or hot side

RAPLOS - Mass contained in the outlet emissions due to rapping (mg/DSCM)

YMELS - Mass entering the last section of the precipitator from adjusted, no-rap calculations (kg/m^3)

YMCLS - Mass collected in the last section of the precipitator from adjusted, no-rap calculations (kg/m^3 or mg/DSCM)

YMLLS - Mass leaving the last section of the precipitator from adjusted, no-rap calculations (kg/m^3)

DD - Mass density of the particles (kg/m^3)

RNS - Number of particles per cubic meter of gas in a given size band that are contained in the emissions due to rapping (#/m^3)

EFFWR - Mass collection fraction for a given particle size containing all corrections and adjustments

CRNP - Number of particles per cubic meter of gas in a given size band that are collected after rapping (#/m^3)

COREFF - Mass collection efficiency for a given particle size containing all corrections and adjustments (%)

WYP - Migration velocity for a given particle size containing all corrections and adjustments (cm/sec)

CPENTR - Percent penetration of a given particle size containing all corrections and adjustments (%)

CPCTOT(I) - Percentage by mass in a given size band contained in the no-rap + rap emissions (%)

SL - Number of particles per cubic meter of gas of a given particle size band exiting the precipitator under no-rap conditions ($\#/m^3$)

RAD(I) - Radii of the different particle sizes (m)

WSL(I) - Weight per cubic meter of gas of particles in a given size band exiting the precipitator under no-rap conditions (kg/m^3)

ENDPT(I) - Particle diameters in the inlet cumulative percent by mass distribution (μm and m)

DLD - Value of the quantity $[\Delta\log_{10}D]$ for a given particle size band in the size distribution histogram

DMDLD(I) - Value of the quantity $[\Delta M/\Delta\log_{10}D]$ for the different particle size bands in the outlet emissions under no-rap conditions (mg/DSCM)

RDMDLD(I) - Value of the quantity $[\Delta M/\Delta\log_{10}D]$ for the different particle size bands in the outlet emissions due to rapping only (mg/DSCM)

CDMDLD(I) - Value of the quantity $[\Delta M/\Delta\log_{10}D]$ for the different particle size bands in the outlet emissions under no-rap + rap conditions (mg/DSCM)

CCF(I) - Cunningham correction factor for the different particle sizes

ETAO - Estimated or design overall mass collection efficiency (%)

ZMMDI - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMI - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

NDIST - Indicator which specifies whether the user is to supply the inlet particle size distribution or the program is to calculate a log-normal distribution

GFIT - Linear-correlation coefficient obtained in the log-normal fit of the inlet particle size distribution

PRCUNR(I) - Cumulative percentage by mass as a function of particle size for the outlet emissions under no-rap conditions (%)

SUMNR - Summation over the different particle size bands of the percentage by mass contained in each size band for the outlet emissions under no-rap conditions (%)

ZMDL - Fitted mass median diameter of the outlet no-rap emissions based on a log-normal distribution (μm)

SIGMO - Fitted geometric standard deviation of the outlet no-rap emissions based on a log-normal distribution

ZGFIT - Linear-correlation coefficient obtained in the log-normal fit of the outlet no-rap emissions

COREFW - Precipitation rate parameter under no-rap + rap conditions (cm/sec)

WZ - Precipitation rate parameter under no-rap conditions (cm/sec)

PRCUC(I) - Cumulative percentage by mass as a function of particle size for the outlet emissions under no-rap + rap conditions (%)

SUMC - Summation over the different particle size bands of the percentage by mass contained in each size band for the outlet emissions under no-rap + rap conditions (%)

CZMDL - Fitted mass median diameter of the outlet no-rap + rap emissions based on a log-normal distribution (μm)

CSIGMO - Fitted geometric standard deviation of the outlet no-rap + rap emissions based on a log-normal distribution

CGFIT - Linear-correlation coefficient obtained in the log-normal fit of the outlet no-rap + rap emissions

M - Index which runs over the different particle size bands

NONID - Number of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered

NRAPD - Number of rapping puff particle size distributions to be considered

PATHL - Pathlength for calculation of opacity (m). If PATHL = 0, no opacity calculations will be performed

NTIMES - Indicator used to avoid repeating many opacity calculations

CMR - Real part of refractive index

CMI - Imaginary part of refractive index

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE OPAC USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

RAPLOS - Mass contained in the outlet emissions due to rapping (mg/DSCM and g/ACM)

YMLLS - Mass leaving the precipitator from adjusted, no-rap calculation (kg/m^3 and g/ACM)

CONVF - Conversion factor for kg/ACM to mg/DSCM

DIAM - Particle diameter (m and μm)

CDMDLD - Differential mass for the rap + no-rap case (mg/DSCM and g/ACM)

NTIMES - Indicator used to avoid repeating many calculations

NCOMPS - Number of compositions (indices of refraction) for which the opacity is to be calculated

NLAMDA - Number of wavelength increments for variable composition

NWAVES - Number of wavelengths at which calculation is to be performed (= 1 or 10)

CMR - Real part of index of refraction

CMI - Imaginary part of index of refraction

JJ - A counter

M - A counter

UPTOLM - Maximum wavelength in each wavelength band used for variable composition calculations. The minimum wavelength is preset at 400 nm

DD - Mass density of the particles (g/cm^3)

YVLLS - Volume of particles per cubic meter of gas for no-rap case (cm^3/ACM)

VAPLOS - Volume of particles per cubic meter of gas due to rapping (cm^3/ACM)

TOTMAS - Total mass leaving the precipitator for the combined rap + no-rap case (g/ACM)

TOTVOL - Total volume of particles per cubic meter of gas leaving the precipitator for the rap + no-rap case (cm^3/ACM)

NS - Number of particle size bands

DELTAD - Value of $\Delta\log_{10}$ (Diameter) for each particle size band

YOTARA - Total projected area of no-rap effluent particles (m^2/ACM)

DMDLD - Differential mass for the no-rap case (mg/DSCM and g/ACM) and normalized differential projected area for the no-rap case

ROTARA - Total projected area of rapping effluent particles (m^2/ACM)

RDMDLD - Differential mass for the rapping puff (mg/DSCM and g/ACM) and normalized differential projected area for the rapping puff

NCOMP - Composition counter with maximum value NCOMPS

J - A counter

PATHL - Pathlength for calculation of opacity (m)

NNCOMP - Indicator used to avoid repeating many calculations

YTONRP - Total extinction coefficient for the no-rap case (m^{-1})

OFDDMD - Differential extinction coefficient for the no-rap case (m^{-1})

RTONRP - Total extinction coefficient for the rapping puff (m^{-1})

OFDRMD - Differential extinction coefficient for the rapping puff (m^{-1})

OFDTOT - Differential extinction coefficient for the rap + no-rap case (m^{-1})

TOTNRP - Total extinction coefficient for the rap + no-rap case (m^{-1})

YTOSPE - Specific mass extinction coefficient for the no-rap case (m^2/g)

RTOSPE - Specific mass extinction coefficient for the rapping puff (m^2/g)

TOTSPE - Specific mass extinction coefficient for the rap + no-rap case (m^2/g)

YTONRK - Specific particulate volume coefficient for the no-rap case (cm^3/m^2)

RTONRK - Specific particulate volume coefficient for the rapping puff (cm^3/m^2)

TOTNRK - Specific particulate volume coefficient for the rap + no-rap case (cm^3/m^2)

YTOOPA - Opacity for the no-rap case (%)

RTOOPA - Opacity for the rapping puff (%)

TOTOPA - Opacity for the rap + no-rap case (%)

NCOMPP - A counter = NCOMP - 1 used in printing tables

NCOPPP - A counter used in printing tables

NOPRNT - An indicator used to determine how much opacity information is printed

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE RAPPE USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

CMR - Real part of refractive index for opacity calculation

CMI - Imaginary part of refractive index for opacity calculation

SNUCK - Fraction of gas sneakage and/or particle reentrainment without rapping

ZIGGY - Normalized standard deviation of the gas velocity distribution

ZNUMS - Number of stages over which gas sneakages and/or particle reentrainment without rapping occur

NREEN - Indicator which marks the first loop through the rapping cycle so that rapping data may be read

LREEN - Indicator which causes the initialization of several accumulators

LOOPR - Indicator which marks the end of the rapping cycle and returns the precipitator model to its normal processing sequence

TIMRAP - Time at which the rap occurs (min)

TIMER - Time at which the reentrained dust for each increment of the dust size distribution profile exits the precipitator (min)

OLDTIM - Previous value of TIMER (min)

DTIMER - Time interval between each increment of reentrained dust and its predecessor (sec)

MAPRAP - Indicator that shows which sections (and increments) of the precipitator are rapped

REPCT - Fraction of dust layer that is reentrained

NUMBOL - Number of increments in the reentrainment profile

NDAT - Indicator that specifies whether a new reentrainment profile is to be read

BOLFRC - Normalized fraction of dust reentrained in each increment of the reentrainment profile

REMMD - Mass median diameter of the particles reentrained in each increment of the reentrainment profile

RESIG - Geometric standard deviation of the particle size distributions in each increment of the reentrainment profile

BOLTIM - Time interval associated with each increment of the reentrainment profile (sec)

LBOIL - Reentrainment profile increment counter

ACCPEN - Accumulated penetration mass

OLDPEN - Previous value of ACCPEN

AVGPEN - Time averaged value of ACCPEN

NTIMES - Indicator used to avoid repeating many opacity calculations

NUMSEC - Number of electrical sections in the precipitator

RAPI - Indicator used to avoid repeating subroutine calls

NRAP - Indicator used to specify whether dynamic rapping will be used and if so, what data will be printed

DDR - Mass density of the reentrained particles (kg/m^3)

DD - Mass density of the input particles (kg/m^3)

TPMASS - Total penetration mass at the time specified (kg/sec)

TSMASS - Penetration mass due to steady state (no-rap) operation (kg/sec)

TDMASS - Penetration mass at the time specified due to the rap (kg/sec)

TOMASS - Total inlet mass (kg/sec)

PENJ - Fraction of particles in each size band penetrating the precipitator

ONO - Initial number of particles in each size band per cubic meter of gas ($\#/m^3$)

XNO - Number of particles in each size band penetrating the precipitator per cubic meter of gas ($\#/m^3$)

ZXNO - Number of particles in each size band penetrating the precipitator per cubic meter of gas due to no-rap operation ($\#/m^3$)

AWYJ - Derived migration velocity of particles in each size band (cm/sec)

VG - Gas volume flow rate (m^3/sec)

ATOTAL - Total collection plate area of the precipitator (m^2)

XMV - Effective migration velocity in each size band under ideal conditions (m/sec)

DIAM - Particle size diameter (m)

DIA - Particle size diameter (μm)

RAPDST - Array containing number of particles in each size band per cubic meter of gas which are reintroduced into the gas flow in each increment of the precipitator by rapping ($\#/m^3$)

OMASS - Initial particle mass in each size band (kg/sec)

PMASS - Total particle mass in each size band penetrating the precipitator (kg/sec)

SMASS - Non-rapping particle mass in each size band penetrating the precipitator (kg/sec)

DMASS - Rapping particle mass in each size band penetrating the precipitator (kg/sec)

PCTIN - Percent by mass of the different size bands at the inlet

PCNT - Fraction by mass of the different size bands at the inlet

PCTOUT - Percent by mass of the different size bands at the outlet

DLD - Value of ΔlogD used in differential mass calculation

DELTAD(I) - Same as DLD

ENDPT - End points of the particle size bands

DMDLDI - Differential mass at the inlet

DMDLDO - Differential mass at the outlet

DMDLD(I) - Differential mass at the outlet for the no-rap case

RDMDLD(I) - Differential mass at the outlet for the rapping puff

CDMDLD(I) - Combined rap + no-rap differential mass at the outlet

DMDLS(I) - Same as DMDLD(I)

PEN - % penetration in each size band

EFFIC - % efficiency in each size band

PENE - Total instantaneous % penetration and total average % penetration

APCT - Cumulative fraction by mass of the size bands at the outlet

D5W - Calculated mass median diameter of the outlet distribution

SIGGO - Geometric standard deviation of the outlet particle size distribution

GG - Quality of the fit to the mass median diameter calculation

YMLLS - Particle mass penetrating the precipitator due to steady state (no-rap) operation (kg/m^3)

RAPLOS - Particle mass penetrating the precipitator due to the rapping puff (kg/m^3)

PUFMAS - Total penetration for this rapping puff (kg)

PATHL - Path length for calculation of opacity (m)

CONVF - Conversion factor for kg/ACM to mg/DSCM

NOPRNT - Indicator used to determine how much opacity information is printed

NSEC - Precipitator section counter

NSECC - Precipitator increment counter

LSECT - Number of increments in each precipitator section

LAYER(I) - Thickness of deposited dust layer in each precipitator increment (mm)

THICK(I) - Dust layer deposition rate (mm/min)

RAPLAY(I) - Amount of deposited dust in each precipitator increment which gets reentrained due to rapping

RAPSEC - Precipitator section which gets rapped

PCNTR(J) - Mass fraction in each size band of the log-normal distribution of the reentrained dust

CUNITS - Units conversion factor -- inches or meters to mm

AS(I) - Collection plate area in each section (m^2)

RAD(J) - Radii of the different particle sizes (m)

BS(I) - Wire-to-wire spacing in each section (in. or m)

WLS(I) - Total wire length in each section (ft or m)

NWS(I) - Number of wires in each section

LINCS(I) - Incremental length in each section (ft or m)

NNF - Number of increments between rapped section and precipitator outlet

TINC - Time required for gas to travel one increment (sec)

CYCPEN - Total penetration mass for the entire rapping cycle (kg)

NFN - Total number of precipitator increments plus one

CPMASS(I) - Cumulative penetration mass in each size band (kg/sec)

CPEN - % penetration in each size band averaged over the entire rapping cycle

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE CHEKIN USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

DL - Inlet mass loading (kg/m^3)

DLB - Inlet mass loading (grains/ft^3)

PL - Total electrical length of the precipitator (m)

PLB - Total electrical length of the precipitator (ft)

RHO - Resistivity of the collected particulate layer (ohm-m)

RHOCGS - Resistivity of the collected particulate layer (ohm-cm)

NENDPT - Number of particle diameters in the inlet cumulative percent by mass distribution

NDATA - Indicator which determines the type of data set that is to be read into the program

NEST - Indicator which specifies whether to use extensive calculations or estimation procedures in determining precipitator performance

NDIST - Indicator which specifies whether the user is to supply the inlet particle size distribution or the program is to calculate a log-normal distribution

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

NITER - Indicator which determines the maximum number of iterations over a loop that converges on overall mass efficiency or the number of iterations that will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions

NCALC - Indicator which determines whether to use equation (12) for particle charging or the sum of the classical field and diffusion charges

NRAPD - Number of rapping puff particle size distributions to be considered

NEFF - Indicator which determines whether the unadjusted, ideal or adjusted, no-rap efficiency is used to determine the mass reentrained due to rapping

NTEMP - Indicator which specifies whether the precipitator is cold or hot side

NONID - Number of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered

NN - Number of increments in the integration of equation (12)

IFINAL - Indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points

VISKIP - Indicator which determines whether or not a dirty-gas voltage-current curve is calculated in each increment of length

VISAME - Indicator which determines whether or not a clean-gas voltage-current curve is calculated for each of the electrical sections or just the first electrical section

ETAO - Estimated or design overall mass collection efficiency (%)

DD - Mass density of the particles (kg/m^3)

EPS - Relative dielectric constant of the particles

VRATIO - Ratio of the peak applied voltage to the average for use in particle charging

US - Ion mobility at standard temperature and pressure (reduced ion mobility)

FPATH - Factor which scales the ion mean free path

EBD - Electrical breakdown strength of the gas near the collection electrode or the collected particulate layer (V/m)

ARD50(I) - Rapping puff mass median diameters (μm)

ARSIGM(I) - Rapping puff geometric standard deviations

ASNUCK(I) - Fractions of gas sneakage and/or particle reentrainment without rapping

AZIGGY(I) - Normalized standard deviations of the gas velocity distribution

AZNUMS(I) - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur

ENDPT(I) - Particle diameters in the inlet cumulative percent by mass distribution (μm and m)

D50 - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMAP - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

PRCU(L) - Cumulative percent by mass up to each particle size in the inlet particle size distribution (%)

NUMSEC - Number of linear electrical sections in the precipitator

LSECT(I) - Number of length increments in the different linear electrical sections

AS(I) - Collection plate areas for the different linear electrical sections (m^2 or ft^2)

VOS(I) - Applied voltages for the different linear electrical sections (V)

TCS(I) - Total current for the different linear electrical sections (A)

WLS(I) - Total wire length for the different linear electrical sections (ft or m)

ACS(I) - Corona wire radii for the different linear electrical sections (in. or mm)

BS(I) - Wire-to-plate spacing for the different linear electrical sections (in. or m)

NWS(I) - Number of wires per electrical section per gas passage for the different linear electrical sections

SYS(I) - One-half the wire-to-wire spacing for the different linear electrical sections (in. or m)

VGS(I) - Gas volume flow rate for the different linear electrical sections (ft^3/min or m^3/sec)

VGASS(I) - Gas velocity for the different linear electrical sections (ft/sec or m/sec)

TEMPS(I) - Gas temperature for the different linear electrical sections (°F or °C)

PS(I) - Gas pressure in the different electrical sections (atm)

VISS(I) - Gas viscosity for the different linear electrical sections (kg/m-sec)

LINCS(I) - Lengths of the increments taken in the different linear electrical sections (ft or m)

RFS(I) - Roughness factor for the corona wires in the different linear electrical sections

START1(I) - Specified initial current density at which the calculation of a voltage-current curve starts in a given electrical section and the initial current density increment size (A/m^2)

START2(I) - Specified increment in current density which is used in place of START1(I) when the JI1-th point on the voltage-current curve is reached (A/m^2)

START3(I) - Specified increment in current density which is used in place of START2(I) when the JI2-th point on the voltage-current curve is reached (A/m^2)

VSTAR(I) - Estimate of the applied voltage corresponding to the first point on the voltage-current curve as defined by START1(I) (V)

MODL - Indicator which specifies whether metric or mixed-units data is used

PATHL - Optical pathlength for opacity calculation (ft or m)

D - Quantity used to determine if AZNUMS is an integer

LTOT - Total number of increments used in the calculation

PLINC - Calculated overall precipitator length for comparison to PL or PLB

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE INTERN USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

DL - Inlet mass loading (kg/m^3 and grains/ft^3)

PL - Total electrical length of the precipitator (ft and m)

RHO - Resistivity of the collected particulate layer (ohm-cm and ohm-m)

NENDPT - Number of particle diameters in the inlet cumulative percent by mass distribution

NDATA - Indicator which determines the type of data set that is to be read into the program

ITL(I) - Identifying label for the calculations

NEST - Indicator which specifies whether to use extensive calculations or estimation procedures in determining precipitator performance

NDIST - Indicator which specifies whether the user is to supply the inlet particle size distribution or the program is to calculate a log-normal distribution

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

NITER - Indicator which determines the maximum number of iterations over a loop that converges on overall mass efficiency or the number of iterations that will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions

NCALC - Indicator which determines whether to use equation (12) for particle charging or the sum of the classical field and diffusion charges

NRAPD - Number of rapping puff particle size distributions to be considered

NEFF - Indicator which determines whether the unadjusted, ideal or adjusted, no-rap efficiency is used to determine the mass reentrained due to rapping

NTEMP - Indicator which specifies whether the precipitator is cold or hot side

NONID - Number of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered

NN - Number of increments in the Gaussian integration of equation (12)

ETAO - Estimated or design overall mass collection efficiency (%)

DD - Mass density of the particles (kg/m^3)

EPS - Relative dielectric constant of the particles

VRATIO - Ratio of the peak applied voltage to the average for use in particle charging

US - Ion mobility at standard temperature and pressure (reduced ion mobility)

FPATH - Factor which scales the ion mean free path

EBD - Electrical breakdown strength of the gas near the collection electrode or the collected particulate layer (V/m)

ASNUCK(I) - Fractions of gas sneakage and/or particle reentrainment without rapping

AZIGGY(I) - Normalized standard deviations of the gas velocity distribution

AZNUMS(I) - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur

ENDPT(I) - Particle diameters in the inlet cumulative percent by mass distribution (μm)

D50 - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMAP - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

NUMSEC - Number of linear electrical sections in the precipitator

LSECT(I) - Number of length increments in the different linear electrical sections

AS(I) - Collection plate areas for the different linear electrical sections (ft^2)

VOS(I) - Applied voltages for the different linear electrical sections (V)

TCS(I) - Total current for the different linear electrical sections (A)

WLS(I) - Total wire length for the different linear electrical sections (ft^2)

ACS(I) - Corona wire radii for the different linear electrical sections (in.)

BS(I) - Wire-to-plate spacing for the different linear electrical sections (in.)

NWS(I) - Number of wires per electrical section per gas passage for the different linear electrical sections

SYS(I) - One-half the wire-to-wire spacing for the different linear electrical sections (in.)

VGS(I) - Gas volume flow rate for the different linear electrical sections (ft^3/min)

VGASS(I) - Gas velocity for the different linear electrical sections (ft/sec)

TEMPS(I) - Gas temperature for the different linear electrical sections (°F)

PS(I) - Gas pressure in the different electrical sections (atm)

VISS(I) - Gas viscosity for the different linear electrical sections (kg/m-sec)

LINCS(I) - Lengths of the increments taken in the different linear electrical sections (ft)

NS - Number of particle size bands

NOPRNT - Indicator which specifies whether details of particle charging and opacity are printed

PATHL - Optical path length for opacity calculation

NINT - SCA counter for the internal data set

CD - Average charge density at the plate (nA/cm^2)

DV - Total volume of particles per cubic meter of gas [m^3 (particles)/m^3 (gas)]

APPENDIX C

COMPLETE LISTING OF THE COMPUTER PROGRAM

```
C                        ********************************************************
C                        *                                                      *
C                        *               E.P.A.-SO.R.I. ESP MODEL               *
C                        *  THIS PROGRAM IS DESIGNED TO COMPUTE PERFORMANCE    *
C                        *  OF A WIRE-PLATE PRECIPITATOR USING DESIGN AND      *
C                        *  OPERATING PARAMETERS. THE PROGRAM WAS DEVELOPED BY *
C                        *  PERSONNEL OF THE SOUTHERN RESEARCH INSTITUTE FOR   *
C                        *  DR. LES SPARKS OF THE PARTICULATE TECHNOLOGY       *
C                        *  BRANCH, INDUSTRIAL ENVIRONMENTAL RESEARCH LAB,     *
C                        *  ENVIRONMENTAL PROTECTION AGENCY, PROJECT OFFICER.  *
C                        *            REVISION 3         APRIL 1982             *
C                        *                                                      *
C                        ********************************************************
C
C
      REAL  NWIRE,LTHICK,JPART,JION,LINC,NWS,LINCS,LAYER
      INTEGER VISKIP,VISAME,RAPI,RAPSEC
      DIMENSION CHKSUM(20),QSCH(20)
      DIMENSION EFS(99),VERGE(99),NXD(99)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK4/NS
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      COMMON/BLK7/XDC(99,20)
      COMMON/BLK8/EAVG(30),CHFID(30)
      COMMON/BLK9/ECOLL(30)
      COMMON/BLK10/ECLEAN(30)
      COMMON/BLK11/ENDPT(21),NENDPT
      COMMON/BLK12/ARD50(10),ARSIGM(10),ASNUCK(15),AZNUMS(15),AZIGGY(15)
      COMMON/BLK13/VCOOP(15,15),ICYC,NSCT,ICOOP,VSTR(15,15,99)
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK15/NPRINT,NSECT,SLNGTH,A,VO,TC,B,AC,WL,CL,CD,ET,SY,
     1VGAS,P,VIS,W,LINC,XPI,RIOVR,EPLT,AFID,XCD,ZMD,ZWT,
     2WT,LTHICK,JPART,JION,I,ROVRI
      COMMON/BLK16/NCALC,NI,VRATIO,NF
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK18/SCOREF,CZMDL,CSIGMO,NRUN,SNUCK,ZIGGY,RMMD,RSIGMA
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP,
     2PATHL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
      COMMON/BLK20/SCHARG,CHRFID,TIMEI,TIMEF,V,FACTRE,RSIZE,CNUMBR,J,II,
     1ITER,OLDQF(20),OLDQT(20),SOLDQF(20),SOLDQT(20)
      COMMON/BLK23/BOLFRC(15,5),BOLTIM(15),REMMD(15,5),LBOIL,NUMBOL,     RAP
     1 RESIG(5),PUFMAS,OLDPEN,CYCPEN                                     RAP
      COMMON/BLK24/RAPI,MAPRAP(45),TIMER,LAYER(45),DDRAP,                RAP
     1 RAPLAY(45),PCNTR(21),SMASS(21),TSMASS,AVGPEN,ACCPEN,OLDTIM,LREEN, RAP
     2 ZXNO(20),REPCT,CPMASS(20)                                          RAP
      COMMON/BLK25/RAPDST(45,20),NREEN,THICK(99),TINC,LOOPR,DMDLS(20)     RAP
      COMMON/GAUSS/T(3),WGAUS(3)
      COMMON/OPACTY/CMR(10),CMI(10),UPTOLM(10),NTIMES,NCOMP,NNCOMP        OPAC
     1,DELTAD(20),DMDLD(20),RDMDLD(20),CDMDLD(20),TOTOPA(2),TOTNRP(2)     OPAC
      EXTERNAL RATE
C    DEFINE SOURCE AND DESTINATION DEVICES
      NREAD=2
      NPRNT=3
C
C    CONSTANTS
C
      PI = 3.1415927
      E = 1.6E-19
      BC=1.38E-23
      EPSO = 8.85E-12
      CMKS=4.*PI*EPSO
      NDSET=0
 4000 CONTINUE
C
      READ(NREAD,5) NENDPT,NDATA,NRAP,MODL,NOPRNT,PATHL,NCOMPS,NWAVES
     1,NLAMDA
    5 FORMAT(5I2,F5.2,3(3X,I2))
      IF(MODL.EQ.2)GO TO 100                                              INT
      IF(NENDPT-99) 4500,9999,9999
 4500 CONTINUE
      IF(MODL.NE.1)PATHL=PATHL*.305
      NS=NENDPT-1
      READ(NREAD,7) ITL
    7 FORMAT(40A2)
      GO TO(9400,9401,9402,9403),NDATA
 9400 CONTINUE
      READ(NREAD,4864) NEST,NDIST,NVI,NX,NY,NITER,NCALC,NRAPD,NEFF,
     1NTEMP,NONID
 4864 FORMAT(11I2)
      IF(MODL.EQ.3.AND.NVI.EQ.1)GO TO 100                                 INT
      NX1=NX-1
      IF(NVI.EQ.3)NVI=1
      IF(NVI.EQ.4)NVI=2                                                   E2
      IF(NCALC.EQ.0) READ(NREAD,5) NN,NUMINC
      IF(NVI.EQ.2) READ(NREAD,8530) IFINAL,JI1,JI2,VISKIP,VISAME          E2
 8530 FORMAT(5I2)                                                         E2
      READ(NREAD,6) DL,PL,ETAO,DD,EPS,VRATIO,US,FPATH,EBD,RHO
    6 FORMAT(9F8.0,E8.2)
C
C          CONVERSION
C
      IF(MODL.EQ.1)GO TO 1000
      PL = PL * 0.305
      DL = DL * 2.29E-03
 1000 CONTINUE
      RHO = RHO/100.0
      DV = DL / DD
C
      IF(NRAPD.GT.1) READ(NREAD,8531) (ARD50(I),ARSIGM(I),I=2,NRAPD)
 8531 FORMAT(10(2F4.0))
      READ(NREAD,8532) (ASNUCK(I),AZIGGY(I),AZNUMS(I),I=1,NONID)
 8532 FORMAT(6(3F4.0))
      READ(NREAD,4) (ENDPT(I),I=1,NENDPT)
    4 FORMAT(10F8.0)
 9401 CONTINUE
      IF(NDIST.EQ.2) READ(NREAD,8533) D50,SIGMAP
 8533 FORMAT(2F8.0)
      IF(NDIST.EQ.1) READ(NREAD,4) (PRCU(I),I=1,NENDPT)
      GO TO 110                                                         INT
  100 NINT=0                                                            INT
  101 CALL INTERN (NINT)                                                INT
      IF(NINT.GE.5)GO TO 4000                                           INT
  110 DO 4740 I=1,NS
      DIAM(I)=((ENDPT(I)+ENDPT(I+1))/2.)*1.E-06
      RAD(I)=DIAM(I)/2.
 4740 CONTINUE
      IF(NDIST.EQ.2) GO TO 8521
      DO 3 I=1,NS
      PCNT(I)=(PRCU(I+1)-PRCU(I))*1.E-02
    3 CONTINUE
      CALL LNFIT(PRCU,D50,SIGMAP,GFIT)
      ZMMDI=D50
      SIGMI=SIGMAP
      GO TO 8522
 8521 CONTINUE
      CALL LNDIST(D50,SIGMAP,PRCU,PCNT)
      ZMMDI=D50
      SIGMI=SIGMAP
 8522 IF(MODL.EQ.2)GO TO 8534
      IF(NDATA.GT.1) GO TO 8534
      READ(NREAD,770) NUMSEC,(LSECT(I),I=1,NUMSEC)
  770 FORMAT(I2,10I2)
      DO 1143 NSECT=1,NUMSEC
      READ(NREAD,762) AS(NSECT),VOS(NSECT),TCS(NSECT),WLS(NSECT),
     1ACS(NSECT),BS(NSECT),NWS(NSECT),SYS(NSECT),VGS(NSECT)
     2,VGASS(NSECT),TEMPS(NSECT),PS(NSECT),VISS(NSECT),LINCS(NSECT)
  762 FORMAT(7(E11.4))
      IF(NVI.EQ.1) GO TO 1143                                           E2
      READ(NREAD,762) RFS(NSECT),START1(NSECT),START2(NSECT),START3     E2
     1(NSECT),VSTAR(NSECT)                                              E2
 1143 CONTINUE
      GO TO 8534
 9402 CONTINUE
      READ(NREAD,9410) (VGS(I),VGASS(I),I=1,NUMSEC)
 9410 FORMAT (3(2E11.4))
      GO TO 8534
 9403 CONTINUE
      READ(NREAD,9410) (VOS(I),TCS(I),I=1,NUMSEC)
 8534 CONTINUE
```

```
      LK=0
      WRITE(NPRNT,17)
   17 FORMAT('1')
      NI = 2*NY - 2
      NREEN = 0
      LREEN = 0                                                         RAP
      LOOPR = 0                                                         RAP
      NF=0
      DO 4649 KA=1,NUMSEC
      NF=NF+LSECT(KA)
 4649 CONTINUE
C
      DO 1 I = 1 ,NS
      VOL(I) = PCNT(I) * DV
    1 CONTINUE
      NPRINT=0
      IF(NVI.EQ.1) ITER=0
      ICYC=1
      DO 304 I=1,NF                                                     RAP
      DO 303 J=1,NS                                                     RAP
  303 RAPDST(I,J) = 0.                                                  RAP
  304 CONTINUE                                                          RAP
  305 CONTINUE
      IF(NVI.EQ.1) ITER=ITER+1
      DO 9 I = 1, NS
      ONO(I) = VOL(I)/ ( 4./3. * PI * RAD(I)**3 )
    9 CONTINUE
      CALL PRTINP
  310 DO 311 J=1,NS
      DXS(J) = 0.
  311 XNO(J) = ONO(J)
      LK=1
      ZWT=0.
      RATIO=(EPS-1.)/(EPS+2.)
      G=EPS+2.
      INDEX=0
      NSECT=1
C
C***********************************************************************
C
C      START  INCREMENTAL ANALYSIS OF PRECIPITATOR
C
C***********************************************************************
C
      DO 3000 I=1,NF
      NCOOP=0
      ICOOP=2
      NSCT=I
      DO 312 J=1,NS                                                     RAP
  312 XNO(J) = XNO(J) + RAPDST(I,J)                                     RAP
      IF(NVI.EQ.2) ITER=0                                               E2
      INDEX=INDEX+1
      IF(I.EQ.1) GO TO 761
      IF(INDEX-LSECT(NSECT)) 760,760,761
  761 CONTINUE
      NCOOP=1
      NPRINT=1
      IF(I.EQ.1) GO TO 760
      NSECT=NSECT+1
      INDEX=1
  760 CONTINUE
      IF(NCOOP.NE.1) GO TO 764
      IF(MODL.EQ.1)GO TO 1005
      A=AS(NSECT)*9.3E-02
      WL=WLS(NSECT)*0.305
      AC=ACS(NSECT)*2.54E-02
      SX=BS(NSECT)*2.54E-02
      SY=SYS(NSECT)*2.54E-02
      VG=VGS(NSECT)*4.73E-04
      VGAS=VGASS(NSECT)*.305
      TEMP=TEMPS(NSECT)+459.
      TDK=TEMP/1.8
      LINC=LINCS(NSECT)*0.305
      GO TO 1010
 1005 A=AS(NSECT)
      WL=WLS(NSECT)
      AC=ACS(NSECT)/1000.
      SX=BS(NSECT)
      SY=SYS(NSECT)
      VG=VGS(NSECT)
      VGAS=VGASS(NSECT)
      TDK=TEMPS(NSECT)+273.
      LINC=LINCS(NSECT)
 1010 CONTINUE
      VO=VOS(NSECT)
      TC=TCS(NSECT)
      NWIRE=NWS(NSECT)
      P=PS(NSECT)
      VIS=VISS(NSECT)
      RF=RFS(NSECT)                                                     E2
      START=START1(NSECT)                                               E2
      DSTART=START2(NSECT)                                              E2
      CSTART=START3(NSECT)                                              E2
      VSTART=VSTAR(NSECT)                                               E2
      SLNGTH=FLOAT(LSECT(NSECT))*LINC
      B=SX
C
C CALCULATE ION MEAN FREE PATH
C
      ZMV=8.205E-05*TDK/P
      ZMFP=(8.205E-05*TDK)/(1.414*PI*1.6E-19*6.02E+23*P)
      TMFP=ZMFP*FPATH
      VAVG=SQRT((8.*8.314E+07*TDK)/(3.14*32.))
      VAVC=VAVG/100.
      VC=E**2/(BC*TDK)
      FACTRC=(PI*VAVC)/2.
```

```
C
C    COMPUTE ION MOBILITY CORRECTED FOR TEMPERATURE AND PRESSURE
C
      U=(TDK/273.16)*US*(1.0/P)
      COEFFC=PI*U*E
      TINC=LINC/VGAS
      IF(NVI.EQ.1) GO TO 4675                                            E2
      DTINC = TINC/FLOAT(NI)                                             E2
 4675 CONTINUE
C
C     COMPUTE WEIGHT OF DUST
C
 6988 IF(NREEN.EQ.0) W=DL*VG
      IF(NREEN.EQ.0) GO TO 6991                                          RAP
      IF(I.EQ.1) W = DL*VG                                               RAP
      WREEN = 0.                                                         RAP
      DO 6990 J=1,NS                                                     RAP
 6990 WREEN = WREEN + RAPDST(I,J)*4./3.*PI*RAD(J)**3*DDRAP*VG            RAP
      W = W + WREEN                                                      RAP
 6991 CONTINUE
C
      DO 6993 J=1,NS
      TST=-1.1*RAD(J)/ZMFP
      IF(TST.LE.-87.) TST=-87.0
      CCF(J)=1+(ZMFP/RAD(J))*(1.257+.4*EXP(TST))
 6993 CONTINUE
      IF(NVI.EQ.2) GO TO 4676                                            E2
      ERAVG=VO/SX
      DO 6989 L=1,NS
      QSAT(L)=(4.*PI*EPSO*(RAD(L)+TMFP)**2)*ERAVG*(1.+2.*((EPS-1.)/
     1(EPS+2.))*(RAD(L)/(RAD(L)+TMFP))**3)*VRATIO
 6989 CONTINUE
      R=(E*ERAVG)/(BC*TDK*(EPS+2.))
      RR=(E*ERAVG)/(BC*TDK)
      RG=R*G
 4676 CONTINUE
      IF(NVI.EQ.2) GO TO 4677                                            E2
      IF(NEST.EQ.2) GO TO 4678
      IF(ICYC.EQ.2)GO TO 4678
      VW=-1.*VO
      CALL CHAN(VW,NX,NY,SX,SY,PI,AC,NWIRE)
      ICOOP=1
      GO TO 4678
 4677 CONTINUE                                                           E2
      UEQ=U                                                              E2
      NEC=0                                                              E2
      IF((VISAME.EQ.1).AND.(NSECT.GT.1)) GO TO 5564                      E2
      IF((VISAME.EQ.1).AND.(NDSET.GT.1)) GO TO 5564                      E2
      WRITE(NPRNT,7140) NSECT                                            E2
 7140 FORMAT(//23X,'CLEAN GAS VOLTAGE-CURRENT DENSITY-FIELD AT THE PLATE E2
     1 RELATIONSHIP FOR SECTION NO. ',I2//)                              E2
      IF(NSCT.GE.2)START = VERGE(NSCT-1)                                 E2
      CALL EFLD2(UEQ,AC,VO,SX,SY,NX,NY,AEPLT,TDK,P,RF,                   E2
     1START,DSTART,CSTART,IFINAL,VSTART,VW,ACDNTY,NWIRE,NEC,EBD,JI1,JI2) E2
      IF(MODL.EQ.3)STOP                                                 E2
      VERGE(NSCT)=ACDNTY                                                E2
      DO 7919 NZ=1,NI                                                   E2
      ECLEAN(NZ)=ECOLL(NZ)                                              E2
 7919 CONTINUE                                                          E2
      CDCLN=ACDNTY                                                      E2
 5564 CONTINUE                                                          E2
      VOS(NSECT)=-VW                                                    E2
 4678 CONTINUE
      IF(NVI.EQ.2) TC=CDCLN*A                                           E2
C
C   COMPUTE CURRENT DENSITY
      CD = TC / A
C
C   COMPUTE ELECTRIC FIELD IN DEPOSIT
      ET = CD * RHO
C
C   COMPUTE CURRENT PER  M. OF CORONA WIRE
      CL = TC / WL
C
 764  CONTINUE
      IF(NVI.EQ.1) GO TO 4679                                           E2
      ITER=ITER+1                                                       E2
      USUM=0.                                                           E2
      WSSUM=0.                                                          E2
      RHOSUM=0.                                                         E2
      GO TO 4680                                                        E2
 4679 CONTINUE
      DO 4700 JJ=1,NS
      QSCH(JJ)=Q(JJ)
      IF(I.EQ.1)QSCH(JJ)=QSAT(JJ)*0.5
 4700 CONTINUE
      CALL SPCHG1(SW,ROVRI,QROVRI,XS,ETAPF,DW,QSCH,XNO,W,LSECT,TC,VG,
     1ETAO,FID,AFID,AVGFID,XCD,U,UEQ,NSCT,NSECT,LINC,PL,CD,E,ERAVG,NS
     2,XPI)
      CHRFID=AFID
 4680 CONTINUE
C
C***********************************************************************
C
C          START PARTICLE SIZE LOOP
C
C***********************************************************************
C
      PROT=0.0
      WT = 0.
      JPART=0.
C
C   COMPUTE CHARGE ON EACH PARTICLE AFTER ONE INCREMENT OF TRAVEL
C
      IF(NVI.EQ.1) GO TO 4681                                           E2
      II = 0                                                            E2
      SERAVG = 0.0                                                      E2
 6337 CONTINUE                                                          E2
      II = II + 1                                                       E2
      CHRFID=CHFID(II)                                                  E2
      ERAVG=EAVG(II)                                                    E2
      SERAVG = SERAVG + ERAVG/NI                                        E2
      DO 9130 L=1,NS                                                    E2
      QSAT(L)=(4.*PI*EPSO*(RAD(L)+TMFP)**2)*ERAVG*(1.+2.*((EPS-1.)/     E2
     1(EPS+2.))*(RAD(L)/(RAD(L)+TMFP))**3)*VRATIO                       E2
 9130 CONTINUE                                                          E2
      R=(E*ERAVG)/(BC*TDK*(EPS+2.))                                     E2
      RR=(E*ERAVG)/(BC*TDK)                                             E2
      RG=R*G                                                            E2
 4681 CONTINUE
      DO 2900 J = 1, NS
      IF(NVI.EQ.1) GO TO 4682                                           E2
      OLDQ(J)=Q(J)                                                      E2
      IF(II.NE.1) GO TO 426                                             E2
 4682 CONTINUE
      IF(I.NE.1) GO TO 426
      IF(J.GT.1) GO TO 428
      TIMEI=0.
      XIPC=0.
      IF(NVI.EQ.2) GO TO 4683                                           E2
      TIMEF=TINC
      IF(NCALC.EQ.0) H=TINC/NN
      GO TO 4684                                                        E2
 4683 CONTINUE                                                          E2
      TIMEF=DTINC                                                       E2
      IF(NCALC.EQ.0) H=DTINC/NN                                         E2
 4684 CONTINUE
      GO TO 428
  426 CONTINUE
      IF(NVI.EQ.1) GO TO 4685                                           E2
      IF(J.GT.1) GO TO 429                                              E2
      TIMEI=TIMEF                                                       E2
      IF((ITER.GT.1).AND.(II.EQ.1)) TIMEI=TIMEI-TINC                    E2
      TIMEF=TIMEF+DTINC                                                 E2
      IF(NCALC.EQ.0) H=DTINC/NN                                         E2
  429 CONTINUE                                                          E2
      IF(II.NE.1) GO TO 8242                                            E2
      XIPC=XDC(I-1,J)/1.6E-19                                           E2
      GO TO 8243                                                        E2
 8242 CONTINUE                                                          E2
      XIPC=XDC(I,J)/1.6E-19                                             E2
 8243 CONTINUE                                                          E2
      GO TO 4686                                                        E2
 4685 CONTINUE
      IF(J.GT.1) GO TO 4687
      TIMEI=FLOAT(I-1)*TINC
      TIMEF=FLOAT(I)*TINC
      IF(NCALC.EQ.0) H=TINC/NN
 4687 XIPC=XDC(I-1,J)/1.6E-19
 4686 CONTINUE
  428 CONTINUE
      RSIZE=RAD(J)
      SCHARG=QSAT(J)/1.6E-19
      DCONST=RATIO*RSIZE**3
      V=VC/(RSIZE*CMKS)
      ECONST=3.*RSIZE/(EPS+2.)
      FACTRE=FACTRC*RSIZE**2
      COEFF=(COEFFC*SCHARG)/CMKS
      IF(I.LE.2) GO TO 5850
      IF(NVI.EQ.1) GO TO 5851                                           E2
      IF((II.EQ.1).AND.(ITER.EQ.1)) GO TO 5851                          E2
      GO TO 5852                                                        E2
 5851 CONTINUE
      IF(I.EQ.3) GO TO 5853
      IF(NSECT.EQ.1) GO TO 5680
      IF((INDEX.EQ.1).AND.(VOS(NSECT).GT.VOS(NSECT-1))) GO TO 5850
 5680 CONTINUE
      IF(CHKSUM(J).LE.0.005) GO TO 5854
 5853 CONTINUE
      CHKSUM(J)=(XDC(I-1,J)-XDC(I-2,J))/XDC(I-1,J)
 5852 CONTINUE
      IF(NSECT.EQ.1) GO TO 5681
      IF((INDEX.EQ.1).AND.(VOS(NSECT).GT.VOS(NSECT-1))) GO TO 5850
 5681 CONTINUE
      IF(CHKSUM(J).GT.0.005) GO TO 5850
 5854 CONTINUE
      Q(J)=XDC(I-1,J)
      GO TO 5855
 5850 CONTINUE
      IF((NCALC.EQ.1).OR.(NEST.EQ.2)) GO TO 8180
      CALL CHARGN(SCHARG,DCONST,ERAVG,V,RSIZE,ECONST,RR,FACTRE,COEFF,
     1CHRFID,RATE,H,XIPC,NN,CNUMBR)
      GO TO 8181
 8180 CONTINUE
      CALL CHGSUM
 8181 CONTINUE
      Q(J)=CNUMBR*1.6E-19
      IF((TIMEI.EQ.0.).AND.(CNUMBR.GT.SCHARG)) Q(J)=SCHARG*1.6E-19
 5855 CONTINUE
      XDC(I,J)=Q(J)
      IF(NVI.EQ.1) GO TO 2900                                           E2
C                                                                       E2
C   COMPUTE MIGRATION VELOCITY FOR EACH SIZE RANGE                      E2
C                                                                       E2
      EMV=(Q(J)*ECOLL(II))/(6.*PI*RAD(J)*VIS)                           E2
      IF(ITER.EQ.1) EMV=(Q(J)*ECLEAN(II))/(6.*PI*RAD(J)*VIS)            E2
      EMV=CCF(J)*EMV                                                    E2
      XMV(J)=EMV                                                        E2
C                                                                       E2
C   COMPUTE EFFICIENCY FOR EACH SIZE RANGE                              E2
C                                                                       E2
      X=(-A*EMV)/(VG*FLOAT(LSECT(NSECT))*FLOAT(NI))                     E2
```

```
C                                                                        E2
      EFF =  1. - EXP( X )                                               E2
C                                                                        E2
C     COMPUTE NUMBER OF PARTICLES REMOVED IN EACH SIZE RANGE             E2
C                                                                        E2
      IF(ITER.EQ.1) GO TO 3761                                           E2
      IF(II.NE.1) GO TO 3763                                             E2
      XNO(J)=OLDXNO(J)                                                   E2
      GO TO 3763                                                         E2
 3761 CONTINUE                                                           E2
      IF(II.NE.1) GO TO 3763                                             E2
      OLDXNO(J)=XNO(J)                                                   E2
 3763 CONTINUE                                                           E2
      DXNO=XNO(J)*EFF                                                    E2
      IF(ITER.NE.NITER) GO TO 3765                                       E2
      DXS(J)=DXS(J)+DXNO                                                 E2
      WSSUM=DXNO*(1.33333*PI*RAD(J)**3)*DD                               E2
      WS(J)=WS(J)+WSSUM                                                  E2
      WT=WT+WSSUM                                                        E2
C                                                                        E2
C   CALCULATE THE CURRENT DENSITY AT THE PLATE DUE TO THE PARTICULATE    E2
      JPART=JPART+(FLOAT(LSECT(NSECT))*VG*DXNO*Q(J)*FLOAT(NI))/A         E2
 3765 CONTINUE                                                           E2
      XNO(J)=XNO(J)-DXNO                                                 E2
C                                                                        E2
 2900 CONTINUE
      IF(NVI.EQ.1) GO TO 9131                                            E2
      CALL SPCHG2(NS,XNO,VIS,RAD,LINC,F,U,ERAVG,DNSION,                  E2
     1DELTNP,SUMMOB,PNUM,RHOP,TCHRG,PMOB,TDNSP,RDNSI,AFID,UEQ,AVGFID,    E2
     2RIOVR,NSCT,XS,ETAO,PL,ETAPF,CCF,XPI,OLDQ,Q,II,NSECT)               E2
      USUM=USUM+UEQ                                                      E2
      RHOSUM=RHOSUM+RIOVR                                                E2
 5676 CONTINUE                                                           E2
      IF(II.LT.NI) GO TO 6337                                            E2
      UEQ=USUM/FLOAT(NI)                                                 E2
      RIOVR=RHOSUM/FLOAT(NI)                                             E2
      IF(I.EQ.1) GO TO 376                                               E2
      IF(RIOVR.GT.0.99) GO TO 375                                        E2
  376 CONTINUE                                                           E2
      IF((VISKIP.EQ.1).OR.(NEST.EQ.2)) GO TO 3187                        E2
      WRITE (NPRNT,7141) I                                               E2
 7141 FORMAT(//23X,'DIRTY GAS VOLTAGE-CURRENT DENSITY-FIELD AT THE PLATE E2
     1 RELATIONSHIP FOR INCREMENT NO. ',I2//)                            E2
      NEC=1                                                              E2
      START=START1(NSECT)*(UEQ/U)                                        E2
      IF(NSCT.GE.2)START = VERGE(NSCT-1)                                 E2
      CALL EFLD2(UEQ,AC,VO,SX,SY,NX,NY,AEPLT,TDK,P,RF,                   E2
     1START,DSTART,CSTART,IFINAL,VSTART,VW,ACDNTY,NWIRE,NEC,EBD,JI1,JI2) E2
      VERGE(NSCT) = ACDNTY                                               E2
      GO TO 3188                                                         E2
 3187 CONTINUE                                                           E2
      ACDNTY=CDCLN*(UEQ/U)                                               E2
 3188 CONTINUE                                                           E2
```

```
      EPLT=-1.*AEPLT                                                     E2
      XCD=ACDNTY*100000.                                                 E2
  375 CONTINUE                                                           E2
      IF(ITER.NE.NITER) GO TO 1050                                       E2
      IF(INDEX.EQ.1) SUMCD=0.                                            E2
      IF(INDEX.EQ.1) SUMVO=0.                                            E2
      SUMCD=SUMCD+ACDNTY                                                 E2
      SUMVO=SUMVO-VW                                                     E2
      IF(INDEX.EQ.LSECT(NSECT)) TCS(NSECT)=(SUMCD*A)/FLOAT(LSECT(NSECT)) E2
      IF(INDEX.EQ.LSECT(NSECT)) VOS(NSECT)=SUMVO/FLOAT(LSECT(NSECT))     E2
 1050 CONTINUE                                                           E2
      IF(ITER.LT.NITER) GO TO 764                                        E2
      JPART=JPART/FLOAT(NI)                                              E2
      GO TO 4688                                                         E2
 9131 CONTINUE
      IF(UEQ.LT.1.0E-4)UEQ=1.0E-4
      IF(INDEX.EQ.1) GO TO 377
      IF(UEQ.NE.1.0E-4) GO TO 9133
      IF(UEQ.EQ.1.0E-4)EPLT=SKIP
      GO TO 9132
 9133 CONTINUE
      SIGMA=OROVRI-ROVRI
      SIGMA=ABS(SIGMA)
      IF(SIGMA.LT..01) GO TO 9132
  377 CONTINUE
      IF(NEST.EQ.2) GO TO 8182
      RF=1.                                                              E2
      IF(ICYC.EQ.2)GO TO 3775
      IF(I.GT.1)GO TO 3771
      RELD = 293./TDK*P
      ROC = 100.*AC
      EORO = ROC*(30.*RELD+9.*SQRT(RELD/ROC))*1000.
      VERGE(I) = -2.*CD*SY/PI/UEQ/EORO
      GO TO 3775
 3771 VERGE(I) = VERGE(I-1)
 3775 CALL EFLD1(UEQ,CD,AC,VO,SX,SY,NX,NY,TDK,P,AEPLT,VERGE(I),VERGE(I))
      EPLT=-1.*AEPLT
      GO TO 8183
 8182 CONTINUE
      EPLT=ERAVG/1.75
 8183 CONTINUE
      SKIP=EPLT
      GO TO 91323
 9132 GO TO (91321,91323),ICYC
91321 VERGE(I) = VERGE(I-1)
      DO 91322 III=1,NX1
      DO 91322 JJJ=1,NY
91322 VSTR(III,JJJ,NSCT) = VSTR(III,JJJ,NSCT-1)
91323 OROVRI = ROVRI
      DO 2965 J=1,NS
C
C   COMPUTE MIGRATION VELOCITY FOR EACH SIZE RANGE
C
```

```
      EMV=(Q(J)*EPLT)/(6.*PI*RAD(J)*VIS)
      EMV=CCF(J)*EMV
      XMV(J)=EMV
C
C   COMPUTE EFFICIENCY FOR EACH SIZE RANGE
C
      X=(-A*EMV)/(VG*FLOAT(LSECT(NSECT)))
C
      EFF =  1. - EXP( X )
C
C     COMPUTE NUMBER OF PARTICLES REMOVED IN EACH SIZE RANGE
C
      DXNO=XNO(J)*EFF
      DXS(J)=DXS(J)+DXNO
      XNO(J)=XNO(J)-DXNO
      IF(DXNO.LT.1.0E-15)DXNO=0.0
      WS(J)=DXNO*(1.33333*PI*RAD(J)**3)*DD
      WT=WT+WS(J)
C
C   CALCULATE THE CURRENT DENSITY AT THE PLATE DUE TO THE PARTICULATE
      JPART=JPART+(FLOAT(LSECT(NSECT))*VG*DXNO*Q(J))/A
C
 2965 CONTINUE
 4688 CONTINUE
      ZWT=ZWT+WT
C
C   CALCULATE THE CURRENT DENSITY AT THE PLATE DUE TO IONS
      JION=CD-JPART
C
C   CALCULATE THICKNESS OF DUST LAYER IN (MM/MIN)/INCREMENT
C
      LTHICK=(WT*VG*FLOAT(LSECT(NSECT))*6.0E+04)/(1.0E+03*A)
      THICK(I)=LTHICK                                                   RAP
C
C  CALCULATE MMD AND WEIGHT COLLECTED FOR EACH INCREMENT
C
      ZTM=0.
      DO 2901 J=1,NS
      ZTM=ZTM+WS(J)
      CZA=ZTM/WT
      IF(CZA-0.5)2901,2901,2902
 2901 CONTINUE
 2902 CZB=(ZTM-WS(J))/WT
      TL1=CZA-CZB
      TL2=0.50-CZB
      KJ=J-1
      IF(KJ)2910,2910,2911
 2910 ZMD=DIAM(J)
      GO TO 2912
 2911 ZMD=DIAM(KJ)+(TL2/TL1)*(DIAM(J)-DIAM(KJ))
 2912 CONTINUE
      IF(NVI.EQ.2) ERAVG = SERAVG                                       E2
      IF(NREEN.NE.0.OR.LREEN.NE.0) GO TO 3000                           RAP
      IF(NOPRNT.GE.2)GO TO 3000
      CALL PRTINC
 3000 CONTINUE
C
      ETC=(ZWT/DL)*100.
      IF(NVI.EQ.2) GO TO 1620                                           E2
      IF(NREEN.NE.0.OR.LREEN.NE.0) GO TO 1621                           RAP
      DIFF=ETC-ETAO
      DIFF=ABS(DIFF)
      IF(DIFF-0.05)60,300,300
  300 CONTINUE
      WRITE(NPRNT,8656) ETAO,ETC
 8656 FORMAT(/' EST. EFFICIENCY =',F6.2,5X,'UNCORRECTED COMPUTED EFFICIE
     1NCY =',F6.2)
      IF(ITER.EQ.NITER) GO TO 1621
      ETAO=ETC
      ICYC=2
      GO TO 305
   60 WRITE(NPRNT,1619) ETAO,ETC
 1619 FORMAT(/' EST EFFICIENCY =',F6.2,5X,'COMPUTED EFFICIENCY =',
     1 F6.2,5X,'CONVERGES')
      GO TO 1621
 1620 CONTINUE
      WRITE(NPRNT,1622) ETAO,ETC
 1622 FORMAT(/' DESIGN EFFICIENCY =',F6.2,5X,'UNCORRECTED COMPUTED EFFIC
     1IENCY =',F6.2)
 1621 CONTINUE
      ATOTAL=0.
      VG=0.
      DO 4985 I=1,NUMSEC
      ATOTAL=ATOTAL+AS(I)
 4985 VG=VG+VGS(I)
      IF(MODL.NE.1)ATOTAL=ATOTAL*9.3E-02
      IF(MODL.NE.1)VG = VG * 4.73E-04
      VG=VG/FLOAT(NUMSEC)
      IF(NRAP.NE.0)GO TO 9995                                           RAP
      IF(NOPRNT.NE.0)GO TO 9994
      CALL PRTCHG
 9994 CALL ADJUST
      IF(MODL.EQ.2.AND.NINT.LT.4)GO TO 101                              INT
      GO TO 4000
 9995 CALL RAPPE                                                        RAP
      IF(LOOPR.EQ.1)GO TO 310                                           RAP
      GO TO 4000                                                        RAP
 9999 STOP 11111
      END
      SUBROUTINE PRTINP
      REAL LINCS,NWS
      INTEGER VISKIP,VISAME
      DIMENSION IBLNK(21)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      COMMON/BLK11/ENDPT(21),NENDPT
      COMMON/BLK12/ARD50(10),ARSIGM(10),ASNUCK(15),AZNUMS(15),AZIGGY(15)
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK16/NCALC,NI,VRATIO,NF
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP,
     2PATHL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
      DATA IBLNK/21*' '/
      IF(LK) 111,111,160
  111 CONTINUE
      WRITE(NPRNT,5850)
 5850 FORMAT(40X,'*************************************')
      WRITE(NPRNT,5851)
 5851 FORMAT(40X,'*',35X,'*')
      WRITE(NPRNT,5852)
 5852 FORMAT(40X,'*',9X,'E.P.A. ESP MODEL',10X,'*')
      WRITE(NPRNT,5851)
      WRITE(NPRNT,5853)
 5853 FORMAT(40X,'*',4X,'I.E.R.L.-R.T.P. AND SO.R.I.',4X,'*')
      WRITE(NPRNT,5851)
      WRITE(NPRNT,5854)
 5854 FORMAT(40X,'*',12X,'REVISION III',11X,'*')
      WRITE(NPRNT,5851)
      WRITE(NPRNT,5850)
      NDSET=NDSET+1
      DLB=DL/2.29E-03
      PLB=PL/0.305
      RHOCGS=100.*RHO
      NCARD=0
      WRITE(NPRNT,2000) NDSET
 2000 FORMAT(//'  PRINTOUT OF INPUT DATA FOR DATA SET NUMBER ',I2//)
      CALL CHEKIN                                                       CHEK
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
 2001 FORMAT(//'  DATA ON CARD NUMBER ',I3//)
      IF(MODL.EQ.1)GO TO 2002
      PATHLF = PATHL/.305
      WRITE(NPRNT,1000) NENDPT,NDATA,NRAP,MODL,NOPRNT,PATHLF,NCOMPS,
    1NWAVES,NLAMDA
1000 FORMAT('  NENDPT = ',I2,'   NDATA = ',I2,'   NRAP = ',I2,
    1'   MODL = ',I2,'   NOPRNT = ',I2,'   PATHL = ',F5.2,' FT',
    2'   NCOMPS = ',I2,'   NWAVES = ',I2,'  NLAMDA = ',I2)
     GO TO 2003
2002 WRITE(NPRNT,1050) NENDPT,NDATA,NRAP,MODL,NOPRNT,PATHL,NCOMPS,
    1NWAVES,NLAMDA
1050 FORMAT('  NENDPT = ',I2,'   NDATA = ',I2,'   NRAP = ',I2,
    1'   MODL = ',I2,'   NOPRNT = ',I2,'   PATHL = ',F5.2,' M',
    2'   NCOMPS = ',I2,'   NWAVES = ',I2,'  NLAMDA = ',I2)
2003 NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     WRITE(NPRNT,1001) ITL
1001 FORMAT(2X,40A2)
     GO TO(6000,6001,6002,6002),NDATA
6000 CONTINUE
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     WRITE(NPRNT,1002) NEST,NDIST,NVI,NX,NY,NITER,NCALC,NRAPD,NEFF,
    1NTEMP,NONID
1002 FORMAT('  NEST = ',I2,2X,'NDIST = ',I2,2X,'NVI = ',I2,2X,'NX = '
    1,I2,2X,'NY = ',I2,2X,'NITER = ',I2,2X,'NCALC = ',I2,2X,'NRAPD = ',
    2I2,2X,'NEFF = ',I2,2X,'NTEMP = ',I2,2X,'NONID = ',I2)
     IF(NCALC.NE.0) GO TO 1003
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     WRITE(NPRNT,1004)NN
1004 FORMAT('  NN = ',I2)
1003 CONTINUE
     IF(NVI.EQ.1) GO TO 1005
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     WRITE(NPRNT,1006) IFINAL,JI1,JI2,VISKIP,VISAME
1006 FORMAT('  IFINAL = ',I2,2X,'JI1 = ',I2,2X,'JI2 = ',I2,2X,'VISKIP =
    1',I2,2X,'VISAME = ',I2)
1005 CONTINUE
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     IF(MODL.EQ.1)GO TO 2004
     WRITE(NPRNT,1007) DLB,PLB,ETAO,DD,EPS
1007 FORMAT('  DL = ',F8.5,' GRN/ACF',2X,'PL = ',F8.4,' FT',2X,'ETAO =
    1',F8.5,' %',2X,'DD = ',F8.2,' KG/M**3',2X,'EPS = ',1PE10.3/)
     GO TO 2005
2004 WRITE(NPRNT,1051) DL,PL,ETAO,DD,EPS
1051 FORMAT('  DL = ',F8.5,' KG/ACM',2X,'PL = ',F8.4,' M',2X,'ETAO = '
    1,F8.5,' %',2X,'DD = ',F8.2,' KG/M**3',2X,'EPS = ',1PE10.3/)
2005 WRITE(NPRNT,1008) VRATIO,US,FPATH,EBD,RHOCGS
1008 FORMAT('  VRATIO = ',F8.4,2X,'US = ',F8.6,' M**2/V-SEC',2X,'FPATH
    1= ',F8.4,2X,'EBD = ',F8.0,' V/M',2X,'RHOCGS = ',1PE9.2,' OHM-CM')
     IF(NRAPD.EQ.1) GO TO 1009
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     WRITE(NPRNT,1010) (I,ARD50(I),I,ARSIGM(I),I=2,NRAPD)
```

```
 1010 FORMAT('  ARD50(',I2,') = ',F4.1,' UM',2X,'ARSIGM(',I2,') = ',F4.1
     1/)
 1009 CONTINUE
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      DO 1011 I=1,NONID
      IF(I.EQ.7) NCARD=NCARD+1
      IF(I.EQ.7) WRITE(NPRNT,2001) NCARD
      IF(I.EQ.13) NCARD=NCARD+1
      IF(I.EQ.13) WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,6570) I,ASNUCK(I),I,AZIGGY(I),I,AZNUMS(I)
 6570 FORMAT('  ASNUCK(',I2,') = ',F4.2,2X,'AZIGGY(',I2,') = ',F4.2,2X,'
     1AZNUMS(',I2,') = ',F4.1/)
 1011 CONTINUE
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      NDCARD=2
      IF(NENDPT.LE.10) NDCARD=1
      IF(NENDPT.GT.20) NDCARD=3
      GO TO(1012,1013,1014),NDCARD
 1012 CONTINUE
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=1,NENDPT)
 1015 FORMAT(5(1X,A1,'ENDPT(',I2,') = ',F8.3,' UM',1X)/)
      GO TO 1016
 1013 CONTINUE
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=1,10)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=11,NENDPT)
      GO TO 1016
 1014 CONTINUE
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=1,10)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=11,20)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=21,NENDPT)
 1016 CONTINUE
 6001 CONTINUE
      IF(NDIST.EQ.1) GO TO 1017
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1018) D50,SIGMAP
 1018 FORMAT('  D50 = ',F8.4,' UM',2X,'SIGMAP = ',F8.4)
 1017 CONTINUE
      IF(NDIST.EQ.2) GO TO 1019
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      GO TO(1020,1021,1022),NDCARD
 1020 CONTINUE
      WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=1,NENDPT)
 1023 FORMAT(5(1X,A1,'PRCU(',I2,') = ',F8.4,' %',1X)/)
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```
     GO TO 1024
1021 CONTINUE
     WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=1,10)
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=11,NENDPT)
     GO TO 1024
1022 CONTINUE
     WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=1,10)
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=11,20)
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=21,NENDPT)
1024 CONTINUE
1019 CONTINUE
     IF(NDATA.GT.1) GO TO 5000
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     IF(NUMSEC.GT.5) GO TO 1026
     WRITE(NPRNT,1025) NUMSEC,(IBLNK(I),I,LSECT(I),I=1,NUMSEC)
1025 FORMAT('  NUMSEC = ',I2,2X,5(1X,A1,'LSECT(',I2,') = ',I2))
     GO TO 1027
1026 CONTINUE
     WRITE(NPRNT,1025) NUMSEC,(IBLNK(I),I,LSECT(I),I=1,5)
     WRITE(NPRNT,8570) (IBLNK(I),I,LSECT(I),I=6,NUMSEC)
8570 FORMAT(/5(1X,A1,'LSECT(',I2,') = ',I2))
1027 CONTINUE
     DO 1028 I=1,NUMSEC
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     IF(MODL.EQ.1)GO TO 2006
     WRITE(NPRNT,1029) I,AS(I),I,VOS(I),I,TCS(I),I,WLS(I)
1029 FORMAT('  AS(',I2,') = ',1PE11.4,' FT**2',2X,'VOS(',I2,') = ',1PE1
    11.4,' V',2X,'TCS(',I2,') = ',1PE11.4,' A',2X,'WLS(',I2,') = ',1PE1
    21.4,' FT'/)
     WRITE(NPRNT,1030) I,ACS(I),I,BS(I),I,NWS(I)
1030 FORMAT('  ACS(',I2,') = ',1PE11.4,' IN',2X,'BS(',I2,') = ',1PE11.4
    1,' IN',2X,'NWS(',I2,') = ',1PE11.4)
     NCARD=NCARD+1
     WRITE(NPRNT,2001) NCARD
     WRITE(NPRNT,1031) I,SYS(I),I,VGS(I),I,VGASS(I),I,TEMPS(I)
1031 FORMAT('  SYS(',I2,') = ',1PE11.4,' IN',2X,'VGS(',I2,') = ',1PE11.
    14,' FT**3/MIN',2X,'VGASS(',I2,') = ',1PE11.4,' FT/SEC',2X,'TEMPS('
    2,I2,') = ',1PE11.4,' F'/)
     WRITE(NPRNT,1032) I,PS(I),I,VISS(I),I,LINCS(I)
1032 FORMAT('  PS(',I2,') = ',1PE11.4,' ATM',2X,'VISS(',I2,') = ',1PE11
    1.4,' KG/M-SEC',2X,'LINCS(',I2,') = ',1PE11.4,' FT')
     GO TO 2007
2006 WRITE(NPRNT,1052) I,AS(I),I,VOS(I),I,TCS(I),I,WLS(I)
1052 FORMAT('  AS(',I2,') = ',1PE11.4,' M**2',2X,'VOS(',I2,') = ',1PE11
    1.4,' V',2X,'TCS(',I2,') = ',1PE11.4,' A',2X,'WLS(',I2,') = ',1PE11
```

```
     2.4,' M'/)
      WRITE(NPRNT,1053) I,ACS(I),I,BS(I),I,NWS(I)
 1053 FORMAT('  ACS(',I2,') = ',1PE11.4,' MM',2X,'BS(',I2,') = ',1PE11.4
     1,' M',2X,'NWS(',I2,') = ',1PE11.4)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1054) I,SYS(I),I,VGS(I),I,VGASS(I),I,TEMPS(I)
 1054 FORMAT('  SYS(',I2,') = ',1PE11.4,' M',2X,'VGS(',I2,') = ',1PE11.
     14,' M**3/SEC',2X,'VGASS(',I2,') = ',1PE11.4,' M/SEC',2X,'TEMPS('
     2,I2,') = ',1PE11.4,' C'/)
      WRITE(NPRNT,1055) I,PS(I),I,VISS(I),I,LINCS(I)
 1055 FORMAT('  PS(',I2,') = ',1PE11.4,' ATM',2X,'VISS(',I2,') = ',1PE11
     1.4,' KG/M-SEC',2X,'LINCS(',I2,') = ',1PE11.4,' M')
 2007 IF(NVI.EQ.1) GO TO 1028
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1033) I,RFS(I),I,START1(I),I,START2(I)
 1033 FORMAT('  RFS(',I2,') = ',1PE11.4,2X,'START1(',I2,') = ',1PE11.4,'
     1 A/M**2',2X,'START2(',I2,') = ',1PE11.4,' A/M**2'/)
      WRITE(NPRNT,1034) I,START3(I),I,VSTAR(I)
 1034 FORMAT('  START3(',I2,') = ',1PE11.4,' A/M**2',2X,'VSTAR(',I2,') =
     1 ',1PE11.4,' V')
 1028 CONTINUE
      GO TO 5000
 6002 CONTINUE
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      DO 1035 I=1,NUMSEC
      IF(I.EQ.4) NCARD=NCARD+1
      IF(I.EQ.4) WRITE(NPRNT,2001) NCARD
      IF(I.EQ.7) NCARD=NCARD+1
      IF(I.EQ.7) WRITE(NPRNT,2001) NCARD
      IF(I.EQ.10) NCARD=NCARD+1
      IF(I.EQ.10) WRITE(NPRNT,2001) NCARD
      IF(NDATA.EQ.4) GO TO 1036
      IF(MODL.EQ.1)GO TO 2008
      WRITE(NPRNT,1037) I,VGS(I),I,VGASS(I)
 1037 FORMAT('  VGS(',I2,') = ',1PE11.4,' FT**3/MIN',2X,'VGASS(',I2,') =
     1 ',1PE11.4,' FT/SEC'/)
      GO TO 2009
 2008 WRITE(NPRNT,1056) I,VGS(I),I,VGASS(I)
 1056 FORMAT('  VGS(',I2,') = ',1PE11.4,'  M**3/MIN',2X,'VGASS(',I2,') =
     1 ',1PE11.4,' M/SEC'/)
 2009 GO TO 1035
 1036 CONTINUE
      WRITE(NPRNT,1038) I,VOS(I),I,TCS(I)
 1038 FORMAT('  VOS(',I2,') = ',1PE11.4,' V',2X,'TCS(',I2,') = ',1PE11.4
     1,' A'/)
 1035 CONTINUE
 5000 CONTINUE
      WRITE(NPRNT,1039)
 1039 FORMAT(1H1)
  160 CONTINUE
```

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26600       RETURN
26700       END
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      SUBROUTINE SPCHG1 (SW,ROVRI,DROVRI,XS,ETAPF,DW,QSAT,XNO,W,LSECT,
     1TC,VG,ETAO,FID,AFID,AVGFID,XCD,U,UEQ,I,NSECT,LINC,PL,CD,E,ERAVG,
     2NS,XPI)
      REAL LINC
      DIMENSION DW(99),QSAT(20),XNO(20),LSECT(10)
      IF(I.NE.1) GO TO 1286
      SW = 0.0
      ROVRI=10.
      DROVRI=20.0
C
C   COMPUTE VALUE OF EXPONENT IN DEUTSCH EQUATION FOR THE STATED EFF.
C
      XS=ALOG(100./(100.-ETAO))
C
 1286 CONTINUE
C
C   COMPUTE EFFICIENCY PER LENGTH INCREMENT
C
      ETAPF = 1.-EXP(-LINC*XS/PL)
C
C   COMPUTE AMOUNT OF MATERIAL REMOVED PER INCR.ON A TOTAL WEIGHT BASIS
C
      DW(I) = (W - SW) * ETAPF
      SW = SW + DW(I)
      FID=CD/(E*U*ERAVG)
      SUM=0.0
      DO 1300 L=1,NS
      XXNO=XNO(L)
      IF(XXNO.LT.1.0E-20)XXNO=0.0
 1300 SUM=SUM+QSAT(L)*XXNO
      ZC=200.*(DW(I)/W)*(FLOAT(LSECT(NSECT))/TC)*VG*SUM
      ROVRI=ZC+1.0
      AFID=FID/ROVRI
      AVGFID=AFID*1.E-06
      XCD=CD*100000.
C
C   COMPUTE EFFECTIVE MOBILITY
C
      UEQ=U/ROVRI
C
      XPI=ETAPF*100.
      RETURN
      END
      SUBROUTINE SPCHG2 (NS,XNO,VIS,RAD,LINC,E,U,ERAVG,DNSION,
     1DELTNP,SUMMOB,PNUM,RHOP,TCHRG,PMOB,TDNSP,RDNSI,AFID,UEQ,AVGFID,
     2RIOVR,I,XS,ETAO,PL,ETAPF,CCF,XPI,OLDQ,Q,II,NSECT)
      REAL LINC
      DIMENSION XNO(20),RAD(20),CCF(20),OLDQ(20),Q(20)
      COMMON/BLK7/XDC(99,20)
      COMMON/BLK8/EAVG(30),CHFID(30)
      COMMON/BLK17/NREAD,NPRNT
      IF(I.NE.1) GO TO 1286
C
C   COMPUTE VALUE OF EXPONENT IN DEUTSCH EQUATION FOR THE DESIGN EFF.
C
      XS=ALOG(100./(100.-ETAO))
C
 1286 CONTINUE
C
C   COMPUTE EFFICIENCY PER LENGTH INCREMENT
C
      ETAPF = 1.-EXP(-LINC*XS/PL)
C
      DELTNP=0.
      SUMMOB=0.
      PNUM=0.
      RHOP=0.
      DO 1 J=1,NS
      TCHRG=XNO(J)*XDC(I,J)
      RHOP=RHOP+TCHRG
      SUMMOB=SUMMOB+(TCHRG*CCF(J))/(6.*3.14159*VIS*RAD(J))
      PNUM=PNUM+XNO(J)
      DIFF=XDC(I,J)
      IF((II.NE.1).OR.(I.NE.1)) DIFF=Q(J)-OLDQ(J)
      DELTNP=DELTNP+XNO(J)*DIFF
    1 CONTINUE
      PMOB=SUMMOB/PNUM
      TDNSP=RHOP/1.6E-19
      DNSION=CHFID(II)
      DELTNP=DELTNP/1.6E-19
      RDNSI=DNSION-DELTNP
      IF(RDNSI.GT.0.) GO TO 10
      PIR=DELTNP/DNSION
      RDNSI=0.
      WRITE(NPRNT,11) PIR,I,II
   11 FORMAT(1X,' A FACTOR OF ',F8.3,' MORE IONS NEEDED IN INCREMENT ',I
     12,', INTERVAL ',I2,' TO MEET CHARGING RATE')
   10 CONTINUE
      AFID=RDNSI
      AVGFID=AFID*1.E-06
      UEQ=(U*AFID*E+PMOB*RHOP)/(AFID*E+RHOP)
      RIOVR=(AFID*E)/(AFID*E+RHOP)
      XPI=ETAPF*100.
      RETURN
      END
      SUBROUTINE EFLD1(UEQ,CD,AC,VO,SX,SY,NX,NY,TDK,P,AEPLT,VERGE,
     1CVERGE)
C
C  EVALUATION OF FIELDS, SPACE CHARGE DENSITY, POTENTIAL, AND
C  CURRENT DENSITY FOR A WIRE-PLATE PRECIPITATOR
      REAL MAXJ,MINJ,MOBILT(15,15)
      DIMENSION RHO(15,15),EX(15,15),OLDRO(15,15),OLDV(15,15),
     1CDNSTY(15,15),V(15,15),EY(15,15)
      COMMON/BLK13/VCOOP(15,15),ICYC,NSCT,ICOOP,VSTR(15,15,99)
      COMMON/BLK17/NREAD,NPRNT
      DATA RHO/225*0./,V/225*0./,EX/225*0./,EY/225*0./,OLDRO/225*0./,
     1OLDV/225*0./,CDNSTY/225*0./,MOBILT/225*0./
      DATA PI,EPSO,ITMAX,IZMAX/3.1416,8.854E-12,500,30/
      DATA ECONV,IJMIN,ALPH/5.0E-05,5,0.7/
      VO = -VO
      QZERO = VERGE
C
C  DEFINE GRID OF MOBILITY VALUES
      DO 10 I=1,NX
      DO 10 J=1,NY
      MOBILT(I,J) = UEQ
   10 CONTINUE
C
C  DEFINE MIN AND MAX LIMITS ON CURRENT DENSITY FOR CONVERGENCE
      MAXJ = CD*1.01
      MINJ = CD*.99
C
C  ESTABLISH GRID SPACING
      NX1 = NX-1
      NY1 = NY-1
      AX = SX/NX1
      AY = SY/NY1
      AXS = AX*AX
      AYS = AY*AY
      ASP = AXS*AYS/EPSO
      ASS = 1./(2.*(AXS+AYS))
      DO 20 I=2,NX
      Q1 = 2.*MOBILT(I,1)
      Q2 = Q1*AX
      Q3 = Q1*AY
      Q4 = Q2*AY
      R1 = 2.*MOBILT(I,NY)
      R2 = R1*AX
      R3 = R1*AY
      R4 = R2*AY
      DO 20 J=2,NY1
      P1 = 2.*MOBILT(1,J)
      P2 = P1*AX
      P3 = P1*AY
      P4 = P2*AY
      D1 = 2.*MOBILT(I,J)
      D2 = D1*AX
      D3 = D1*AY
      D4 = D2*AY
   20 CONTINUE
      IZ = 0
      GO TO (30,80),ICYC
   30 GO TO (40,60),ICOOP
   40 DO 50 I=1,NX1
      DO 50 J=1,NY
   50 V(I,J) = VCOOP(I,J)
      GO TO 100
   60 DO 70 I=1,NX1
      DO 70 J=1,NY
   70 V(I,J) = VSTR(I,J,NSCT-1)
      GO TO 100
   80 DO 90 I=1,NX1
      DO 90 J=1,NY
   90 V(I,J) = VSTR(I,J,NSCT)
  100 CONTINUE
  110 IZ = IZ+1
      IF(IZ.LT.IZMAX)GO TO 120
      WRITE(NPRNT,9998)IZMAX
      GO TO 370
  120 CONTINUE
      LL = 0
      ITER = 0
  130 LL = LL+1
      IF(LL.LT.ITMAX)GO TO 140
      WRITE(NPRNT,9999)ITMAX
      GO TO 370
  140 RHO(1.1) = QZERO
      EX(1,1) = 0.
      EY(1,1) = 0.
      DO 150 I=2,NX
      EY(I,1) = 0.
      EX(I,1) = (V(I-1,1)-V(I,1))/AX
      Q5 = -EPSO*EX(I,1)*(Q3-AY*MOBILT(I-1,1))
      Q6 = Q5*Q5
      Q7 = Q1*Q4*EPSO*AY*EX(I,1)*RHO(I-1,1)
      Q8 = -SQRT(ABS(Q6+Q7))
      RHO(I,1) = (Q5+Q8)/Q4
  150 CONTINUE
      DO 160 J=2,NY
      EX(1,J) = 0.
      EY(1,J) = (V(1,J-1)-V(1,J))/AY
      P5 = -EPSO*EY(1,J)*(P2-AX*MOBILT(1,J-1))
      P6 = P5*P5
      P7 = P1*P4*EPSO*AX*EY(1,J)*RHO(1,J-1)
      P8 = -SQRT(ABS(P6+P7))
      RHO(1,J) = (P5+P8)/P4
  160 CONTINUE
      DO 170 I=2,NX
      EY(I,NY) = 0.
      EX(I,NY) = (V(I-1,NY)-V(I,NY))/AX
      R5 = -EPSO*EX(I,NY)*(R3-AY*MOBILT(I-1,NY))
      R6 = R5*R5
      R7 = R1*R4*EPSO*AY*EX(I,NY)*RHO(I-1,NY)
      R8 = -SQRT(ABS(R6+R7))
      RHO(I,NY) = (R5+R8)/R4
  170 CONTINUE
      DO 180 I=2,NX
      DO 180 J=2,NY1
      EX(I,J) = (V(I-1,J)-V(I,J))/AX
      EY(I,J) = (V(I,J-1)-V(I,J))/AY
      D5 = -EPSO*(EX(I,J)*(D3-AY*MOBILT(I-1,J))+EY(I,J)*(D2-AX*MOBILT
     1(I,J-1)))
      D6 = D5*D5
      D7 = D1*D4*EPSO*(AY*EX(I,J)*RHO(I-1,J)+AX*EY(I,J)*RHO(I,J-1))
      D8 = -SQRT(ABS(D6+D7))
      RHO(I,J) = (D5+D8)/D4
  180 CONTINUE
      DO 240 I=1,NX1
      DO 240 J=1,NY
      OLDV(I,J) = V(I,J)
      OLDRO(I,J) = RHO(I,J)
      IF(I.EQ.1.AND.J.EQ.1)GO TO 240
      IF(I.EQ.1.AND.J.NE.1)GO TO 200
      IF(I.NE.1.AND.J.EQ.1)GO TO 220
      IF(J.EQ.NY)GO TO 190
      GO TO 230
  190 V(I,NY) = ASS*(AYS*(V(I-1,NY)+V(I+1,NY))+2.*AXS*V(I,NY-1)+ASP*RHO
     1(I,NY))
      GO TO 240
  200 IF(I.EQ.1.AND.J.EQ.NY)GO TO 210
      V(1,J) =ASS*(2.*AYS*V(2,J)+AXS*(V(1,J+1)+V(1,J-1))+ASP*RHO(1,J))
      GO TO 240
  210 V(1,NY) = ASS*(2.*AYS*V(2,NY)+2.*AXS*V(1,NY-1)+ASP*RHO(1,NY))
      GO TO 240
  220 V(I,1)=ASS*(AYS*(V(I+1,1)+V(I-1,1))+2.*AXS*V(I,2)+ASP*RHO(I,1))
      GO TO 240
  230 V(I,J)=ASS*(AYS*(V(I+1,J)+V(I-1,J))+AXS*(V(I,J-1)+V(I,J+1))+ASP*
     1RHO(I,J))
  240 CONTINUE
C
C  APPLY THE DOMINANT EIGENVALUE METHOD TO ACCELERATE THE CONVERGENCE
      ITER = ITER+1
      DXM = 0.
      DVRM = 0.
      DO 250 I=1,NX1
      DO 250 J=1,NY
      DV = V(I,J)-OLDV(I,J)
      DVR = ABS(DV/V(I,J))
      IF(DVR.GT.DVRM)DVRM=DVR
  250 DXM = DXM+DV**2
      IF(DVRM.LT.ECONV)GO TO 300
      DXM = SQRT(DXM)
      IF(LL-2)260,270,280
  260 DXML = DXM
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      GO TO 130
  270 EIG1 = DXM/DXML
      DXML = DXM
      EIGL = EIG1
      GO TO 130
  280 EIG1 = DXM/DXML
      DXML = DXM
      DEIG = EIG1-EIGL
      EIGL = EIG1
      IF(ABS(DEIG/EIG1).GT.1.0E-03.OR.ITER.LT.IJMIN)GO TO 130
      FCON = ALPH/(1.-EIG1)
      DO 290 I=1,NX1
      DO 290 J=1,NY
  290 V(I,J) = OLDV(I,J)+FCON*(V(I,J)-OLDV(I,J))
      ITER = 0
      GO TO 130
  300 CONTINUE
C
C  COMPUTE THE AVERAGE CURRENT DENSITY AT THE PLATE
      CDNSTY(NX,1) = EX(NX,1)*MOBILT(NX,1)*RHO(NX,1)
      ACDNTY = CDNSTY(NX,1)
  310 DO 320 J=2,NY
      CDNSTY(NX,J) = EX(NX,J)*MOBILT(NX,J)*RHO(NX,J)
      ACDNTY = ACDNTY+CDNSTY(NX,J)
  320 CONTINUE
      ACDNTY = ACDNTY/NY
      IF(ACDNTY.GT.MAXJ)GO TO 330
      IF(ACDNTY.LT.MINJ)GO TO 340
      GO TO 350
  330 QZERO = MINJ/ACDNTY*QZERO
      GO TO 110
  340 QZERO = MAXJ/ACDNTY*QZERO
      GO TO 110
  350 EPLT = EX(NX,1)
      DO 360 J=2,NY
      EPLT = EPLT + EX(NX,J)
  360 CONTINUE
      AEPLT = EPLT/NY
  370 CONTINUE
      CVERGE = QZERO
      VO = -1.*VO
      DO 380 I=1,NX1
      DO 380 J=1,NY
  380 VSTR(I,J,NSCT) = V(I,J)
      RETURN
C
C  FORMATS
 9998 FORMAT('  CURRENT DENSITY DID NOT CONVERGE IN ',I3,' ITERATIONS (E
     1FLD1)')
 9999 FORMAT(1H0,'EFLD1 DID NOT CONVERGE IN ',I4,' ITERATIONS')
      END
      SUBROUTINE EFLD2(UEQ,AC,VO,SX,SY,NX,NY,AEPLT,TDK,P,RF,               E2
     1START,DSTART,CSTART,IFINAL,VSTART,VW,ACDNTY,NWIRE,NEC,EBD,JI1,JI2)
C  EVALUATION OF FIELDS, SPACE CHARGE DENSITY, POTENTIAL, AND
C  CURRENT DENSITY FOR A WIRE-PLATE PRECIPITATOR
      REAL MAXJ,MINJ,MOBILT(15,15),NWIRE,MAXS
      DIMENSION RHO(15,15),EX(15,15),OLDRO(15,15),OLDV(15,15),
     1CDNSTY(15,15),V(15,15),EY(15,15),EAVGS(30),CHFIDS(30),ECOLLS(30)
      COMMON/BLK8/EAVG(30),CHFID(30)
      COMMON/BLK9/ECOLL(30)
      COMMON/BLK13/VCOOP(15,15),ICYC,NSCT,ICOOP,VSTR(15,15,99)
      COMMON/BLK17/NREAD,NPRNT
      DATA RHO/225*0./,V/225*0./,EX/225*0./,EY/225*0./,OLDRO/225*0./,
     1OLDV/225*0./,CDNSTY/225*0./,MOBILT/225*0./
      DATA PI,EPSO,ITMAX,IZMAX/3.1416,8.854E-12, 500,30/
      DATA ECONV,IJMIN,ECONI/5.0E-5,5,1.0E-3/,ALPH/0.7/
      IVCK=0
   10 VO=-VO
      VW=-VSTART
      RO=AC
C
C  COMPUTE RELATIVE AIR DENSITY
      RELD=293./TDK*P
      ROC=100.*RO
      EORO = ROC*RF*(30.*RELD+9.*SQRT(RELD/ROC))*1000.
C
C  DEFINE GRID OF MOBILITY VALUES
      DO 20 I=1,NX
      DO 20 J=1,NY
      MOBILT(I,J) = UEQ
   20 CONTINUE
      SSTART = START
      IF(NSCT.GT.1)GO TO 40
      MAXS=0.
C
C  ESTABLISH GRID SPACING
      NX1=NX-1
      NY1=NY-1
      AX=SX/NX1
      AY=SY/NY1
      AXS=AX*AX
      AYS=AY*AY
      ASP=(AXS*AYS)/EPSO
      ASS=1./(2.*(AXS+AYS))
      DO 21 I=2,NX
      Q1=2.*MOBILT(I,1)
      Q2=Q1*AX
      Q3=Q1*AY
      Q4=Q2*AY
      R1=2.*MOBILT(I,NY)
      R2=R1*AX
      R3=R1*AY
      R4=R2*AY
      DO 21 J=2,NY1
      P1=2.*MOBILT(1,J)
      P2=P1*AX
      P3=P1*AY
      P4=P2*AY
      D1=2.*MOBILT(I,J)
      D2=D1*AX
      D3=D1*AY
      D4=D2*AY
   21 CONTINUE
C
C  USE COOPERMAN APPROX TO GENERATE THE INITIAL VOLTAGE GRID
      CALL CMAN(VW,NX,NY,SX,SY,PI,AC,NWIRE)
      DO 30 I=1,NX
      DO 30 J=1,NY
   30 V(I,J)=VCOOP(I,J)
      GO TO 60
C
C  IF INCREMENT IS OTHER THAN FIRST USE PREVIOUS APPLIED VOLTAGE
C  IN ORDER TO SCALE THE NEW INITIAL VOLTAGE GRID
   40 CON = VW/VWX
      DO 50 I=1,NX
      DO 50 J=1,NY
   50 V(I,J) = VSTR(I,J,NSCT-1)*CON
   60 ANX = 0.06
C
C  DEFINE CURRENT DENSITY ACCORDING TO DESIRED VALUES IN V-I CURVE
      DO 430 II=1,IFINAL
      IF(II.EQ.JI1) START=DSTART
      IF(II.EQ.JI2) START=CSTART
      MAXS = MAXS+START
      IF(II.EQ.1)GO TO 80
C
C  ADJUST APPLIED VOLTAGE USING A POWER LAW CORRELATION WITH
C  CURRENT DENSITY
      VW = OLDVW*(MAXS/ACDNTY)**ANX
      CON = VW/OLDVW
C
C  ADJUST THE VOLTAGE DISTRIBUTION
      DO 70 I=1,NX1
      DO 70 J=1,NY
   70 V(I,J) = V(I,J)*CON
   80 CONTINUE
C
C  DEFINE MIN AND MAX LIMITS OF CURRENT DENSITY FOR CONVERGENCE
      MAXJ = MAXS*1.01
      MINJ = MAXS*0.99
C
C  ESTIMATE THE SPACE CHARGE DENSITY AT THE WIRE
      QZERO = -(2.*(MAXJ+MINJ)*SY*1.0E-03)/(2.*PI*UEQ*ROC*RF*(30.*RELD+
     19.*SQRT(RELD/ROC)))
      IZ = 0
   90 IZ = IZ+1
      IF(IZ.EQ.IZMAX)WRITE(NPRNT,9991) IZMAX
      IF(IZ.EQ.IZMAX) GO TO 355
      LL = 0
      ITER = 0
  100 LL = LL+1
      IF(LL.LT.ITMAX) GO TO 110
      WRITE(NPRNT,9993) ITMAX
      GO TO 355
  110 RHO(1,1) = QZERO
      V(1,1) = VW
      EX(1,1) = 0.
      EY(1,1) = 0.
      DO 120 I=2,NX
      EY(I,1) = 0.
      EX(I,1) = (V(I-1,1)-V(I,1))/AX
      Q5 = -EPSO*EX(I,1)*(Q3-AY*MOBILT(I-1,1))
      Q6 = Q5*Q5
      Q7 = Q1*Q4*EPSO*AY*EX(I,1)*RHO(I-1,1)
      Q7 = ABS(Q7)
      Q8 = -SQRT(ABS(Q6+Q7))
      RHO(I,1) = (Q5+Q8)/Q4
  120 CONTINUE
      DO 130 J=2,NY
      EX(1,J) = 0.
      EY(1,J) = (V(1,J-1)-V(1,J))/AY
      P5 = -EPSO*EY(1,J)*(P2-AX*MOBILT(1,J-1))
      P6 = P5*P5
      P7 = P1*P4*EPSO*AX*EY(1,J)*RHO(1,J-1)
      P7 = ABS(P7)
      P8 = -SQRT(ABS(P6+P7))
      RHO(1,J) = (P5+P8)/P4
  130 CONTINUE
      DO 140 I=2,NX
      EY(I,NY) = 0.
      EX(I,NY) = (V(I-1,NY)-V(I,NY))/AX
      R5 = -EPSO*EX(I,NY)*(R3-AY*MOBILT(I-1,NY))
      R6 = R5*R5
      R7 = R1*R4*EPSO*AY*EX(I,NY)*RHO(I-1,NY)
      R7 = ABS(R7)
      R8 = -SQRT(ABS(R6+R7))
      RHO(I,NY)= (R5+R8)/R4
  140 CONTINUE
      DO 150 I=2,NX
      DO 150 J=2,NY1
      EX(I,J) = -(V(I,J)-V(I-1,J))/AX
      EY(I,J) = -(V(I,J)-V(I,J-1))/AY
      D5=-EPSO*(EX(I,J)*(D3-AY*MOBILT(I-1,J))+EY(I,J)*(D2-AX*MOBILT(I,
     1J-1)))
      D6=D5*D5
      D7=D1*D4*EPSO*(AY*EX(I,J)*RHO(I-1,J)+AX*EY(I,J)*RHO(I,J-1))
      D7=ABS(D7)
      D8=-SQRT(ABS(D6+D7))
      RHO(I,J)=(D5+D8)/D4
  150 CONTINUE
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      DO 210 I=1,NX1
      DO 210 J=1,NY
      OLDV(I,J)=V(I,J)
      OLDRO(I,J)=RHO(I,J)
      IF(I.EQ.1.AND.J.EQ.1)GO TO 210
      IF(I.EQ.1.AND.J.NE.1)GO TO 170
      IF(I.NE.1.AND.J.EQ.1)GO TO 190
      IF(J.EQ.NY)GO TO 160
      GO TO 200
  160 V(I,NY)=ASS*(AYS*(V(I-1,NY)+V(I+1,NY))+2.*AXS*V(I,NY-1)+ASP*RHO
     1(I,NY))
      GO TO 210
  170 IF(I.EQ.1.AND.J.EQ.NY)GO TO 180
      V(1,J)=ASS*(2.*AYS*V(2,J)+AXS*(V(1,J+1)+V(1,J-1))+ASP*RHO(1,J))
      GO TO 210
  180 V(1,NY)=ASS*(2.*AYS*V(2,NY)+2.*AXS*V(1,NY-1)+ASP*RHO(1,NY))
      GO TO 210
  190 V(I,1)=ASS*(AYS*(V(I+1,1)+V(I-1,1))+2.*AXS*V(I,2)+ASP*RHO(I,1))
      GO TO 210
  200 V(I,J)=ASS*(AYS*(V(I+1,J)+V(I-1,J))+AXS*(V(I,J-1)+V(I,J+1))+ASP
     1*RHO(I,J))
  210 CONTINUE
      ITER=ITER+1
      DXM=0.
      DVRM=0.
C
C  APPLY THE DOMINANT EIGENVALUE METHOD FOR ACCELERATION OF CONVERGENCE
      DO 220 I=1,NX1
      DO 220 J=1,NY
      DV=V(I,J)-OLDV(I,J)
      DVR=ABS(DV/V(I,J))
      IF(DVR.GT.DVRM) DVRM=DVR
  220 DXM=DXM+DV**2
      IF(DVRM.LT.ECONV)GO TO 270
      DXM=SQRT(DXM)
      IF(LL-2)230,240,250
  230 DXML=DXM
      GO TO 100
  240 EIG1=DXM/DXML
      DXML=DXM
      EIGL=EIG1
      GO TO 100
  250 EIG1=DXM/DXML
      DXML=DXM
      DEIG=EIG1-EIGL
      EIGL=EIG1
      IF(ABS(DEIG/EIG1).GT.ECONI .OR. ITER.LT.IJMIN)GO TO 100
      FCON=ALPH/(1.-EIG1)
      DO 260 I=1,NX1
      DO 260 J=1,NY
  260 V(I,J)=OLDV(I,J)+FCON*(V(I,J)-OLDV(I,J))
      ITER=0
      GO TO 100
  270 CONTINUE
C
C  COMPUTE THE AVERAGE CURRENT DENSITY AT THE PLATE
      CDNSTY(NX,1)=EX(NX,1)*MOBILT(NX,1)*RHO(NX,1)
      ACDNTY=CDNSTY(NX,1)
  280 DO 290 J=2,NY
      CDNSTY(NX,J)=EX(NX,J)*MOBILT(NX,J)*RHO(NX,J)
      ACDNTY=ACDNTY+CDNSTY(NX,J)
  290 CONTINUE
      ACDNTY=ACDNTY/NY
      IF(IVCK.EQ.1)GO TO 340
      VWOLD=VW
C
C  CHECK IF THE COMPUTED AVERAGE CURRENT DENSITY AT THE PLATE LIES
C  BETWEEN MAXJ AND MINJ; IF NOT ADJUST THE VOLTAGE AT THE WIRE
      IF(ACDNTY.GT.MAXJ)GO TO 300
      IF(ACDNTY.LT.MINJ)GO TO 310
      GO TO 340
  300 VW=VW*(1.+(MAXJ-ACDNTY)/MAXJ)
      GO TO 320
  310 VW=VW*(1.+(MINJ-ACDNTY)/MINJ)
  320 CONTINUE
      TEST=ABS(ACDNTY-(MAXJ+MINJ)/2.)
      TEST1=0.001*ACDNTY
      IF(TEST.LT.TEST1)GO TO 340
C
C  ADJUST THE VOLTAGES AT ALL POINTS IN THE GRID
      CON=VW/VWOLD
      DO 330 I=1,NX1
      DO 330 J=1,NY
  330 V(I,J)=V(I,J)*CON
      GO TO 90
  340 CONTINUE
      EPLT=EX(NX,1)
C
C  CALCULATE THE AVERAGE ELECTRIC FIELD AT THE PLATE
      DO 350 J=2,NY
      EPLT=EPLT+EX(NX,J)
  350 CONTINUE
      AEPLT=EPLT/NY
  355 WRITE(NPRNT,9992)VW,ACDNTY,AEPLT
      IF(II.EQ.1)GO TO 360
      ANX=ALOG(VW/OLDVW)/ALOG(ACDNTY/OLDCD)
  360 IF(ABS(EX(NX,1)).LT.EBD)GO TO 370
      WRITE(NPRNT,9994)VW,ACDNTY
 9994 FORMAT(' THE BREAKDOWN FIELD NEAR THE PLATE IS EXCEEDED AT VW = ',
     1E11.4,' AND ACDNTY = ',E11.4)
      GO TO 440
  370 CONTINUE
      IF(II.GT.1)GO TO 390
      VWX=VW
      DO 380 I=1,NX
      DO 380 J=1,NY
  380 VSTR(I,J,NSCT)=V(I,J)
  390 IF(IVCK.EQ.1)GO TO 440
      IF(ABS(VW).EQ.ABS(VO))GO TO 440
      IF(ABS(VW).GT.ABS(VO))GO TO 400
      OLDVW=VW
      OLDCD=ACDNTY
      GO TO 420
  400 CONTINUE
      MAXS=ACDNTY*(VO/VW)**(1./ANX)
      CON=VO/VW
      DO 410 I=1,NX1
      DO 410 J=1,NY
  410 V(I,J)=CON*V(I,J)
      VW=VO
      IVCK=1
      GO TO 80
  420 CONTINUE
  430 CONTINUE
  440 CONTINUE
      IF(NEC.NE.0)GO TO 510
      K=1
C
C  START LOOP OVER SUBINCREMENTS
      DO 480 J=1,NY1
      RSUM=0.
      ESUM=0.
      DO 470 I=1,NX
      IF(J.EQ.1)GO TO 450
      ESUM=ESUM+(SQRT(EX(I,J)**2+EY(I,J)**2)+SQRT(EX(I,J+1)**2+
     1EY(I,J+1)**2))/(2.*NX)
      GO TO 460
  450 CONTINUE
      ESUM=ESUM+SQRT(EX(I,J+1)**2+EY(I,J+1)**2)/(2.*NX)
      IF(I.EQ.NX) ESUM=ESUM-VO/(2.*SX)
  460 CONTINUE
      RSUM=RSUM-(RHO(I,J)+RHO(I,J+1))/(2.*1.6E-19*NX)
  470 CONTINUE
      EAVGS(K)=ESUM
      CHFIDS(K)=RSUM
      K=K+1
  480 CONTINUE
      NYY=NY1
      DO 490 L=1,NY1
      EAVG(L)=EAVGS(NYY)
      CHFID(L)=CHFIDS(NYY)
      NYY=NYY-1
  490 CONTINUE
      KK=1
      M1=NY1+1
      M2=2*NY1
      DO 500 M=M1,M2
      EAVG(M)=EAVGS(KK)
      CHFID(M)=CHFIDS(KK)
      KK=KK+1
  500 CONTINUE
  510 CONTINUE
      LL=1
      DO 520 NN=1,NY1
      ECOLLS(LL)=-(EX(NX,NN)+EX(NX,NN+1))/2.
      LL=LL+1
  520 CONTINUE
      L1=NY1
      DO 530 L=1,NY1
      ECOLL(L)=ECOLLS(L1)
      L1=L1-1
  530 CONTINUE
      L2=1
      I1=NY1+1
      I2=2*NY1
      DO 540 I=I1,I2
      ECOLL(I)=ECOLLS(L2)
      L2=L2+1
  540 CONTINUE
      VO=-VO
      START=SSTART
C
C  FORMATS
 9991 FORMAT('  CURRENT DENSITY DID NOT CONVERGE IN ',I3,' ITERATIONS (E
     1FLD2)')
 9992 FORMAT(38X,'VW = ',1PE11.4,'  ACDNTY = ',1PE11.4,'  AEPLT = ',
     11PE11.4)
 9993 FORMAT('0EFDL2 DID NOT CONVERGE IN ',I4,' ITERATIONS')
      RETURN
      END
      SUBROUTINE CHARGN(SCHARG,DCONST,EZERO,V,RSIZE,ECONST,RR,
     *FACTOR,COEFF,AFID,RATE,H,YI,NN,Y)
C     FOURTH-ORDER RUNGE-KUTTA SOLUTION FOR THE CHARGE INCREMENT
      COMMON /GAUSS/ T(3),WGAUS(3)
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      Y=YI
      DO 2 I=1,NN
  804 T1=H*RATE(SCHARG,DCONST,EZERO,V,RSIZE,ECONST,
     *RR,FACTOR,COEFF,AFID,Y)
      T2=H*RATE(SCHARG,DCONST,EZERO,V,RSIZE,ECONST,
     *RR,FACTOR,COEFF,AFID,Y+T1/2.)
      T3=H*RATE(SCHARG,DCONST,EZERO,V,RSIZE,ECONST,
     *RR,FACTOR,COEFF,AFID,Y+T2/2.)
      T4=H*RATE(SCHARG,DCONST,EZERO,V,RSIZE,ECONST,
     *RR,FACTOR,COEFF,AFID,Y+T3)
      Y=Y+(T1+2.*T2+2.*T3+T4)/6.
    2 CONTINUE
      RETURN
      END
      FUNCTION RATE(SCHARG,DCONST,EZERO,V,RSIZE,ECONST,
     *RR,FACTOR,COEFF,AFID,NUMBER)
      REAL NUMBER
      COMMON /GAUSS/ T(3),WGAUS(3)
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
C     CALCULATE THETA-ZERO IF NUMBER<SCHARG
      IF(NUMBER-SCHARG)7005,7006,7006
 7005 CALL ARCCOS(NUMBER,SCHARG,THZERO)
      IF(THZERO.LE.1.E-05) GO TO 7006
      IF(1.57-THZERO) 7011,7011,7015
 7015 CONTINUE
      GO TO 7007
 7006 THZERO=0.
C     AND THERE IS NO CONTRIBUTION FROM REGION I
C
C     FIELD ENHANCED DIFFUSION CHARGING RATE IN REGION II
 7007 YFUC=0.0
      CO=DCONST
      CP=(NUMBER*E)/(CMKS*EZERO)
      DO 7002 I=1,3
C     CHANGE ABSCISSA RANGE FROM [THZERO,PI/2] TO [-1,1]
      THETA=T(I)*(PI-2.*THZERO)/4.+(PI+2.*THZERO)/4.
      STHETA=SIN(THETA)
      CTHETA=COS(THETA)
      C1=CP/CTHETA
      CALL ZERO(C1,CO,RZERO)
 7024 ARG1=-(NUMBER*V*(RZERO-RSIZE)/RZERO +
       1 (ECONST - RZERO + DCONST/RZERO**2)*RR*CTHETA)
      IF(ABS(ARG1).GT.30.0) GO TO 7025
      YVAL=EXP(ARG1)*STHETA
      GO TO 7026
 7025 YVAL=0.
 7026 CONTINUE
 7001 YFUC=YFUC+WGAUS(I)*YVAL
 7002 CONTINUE
      YFUC=YFUC*(PI-2.*THZERO)/4.
      RATE2=YFUC*FACTOR*AFID
      GO TO 7012
 7011 RATE2=0.
 7012 CONTINUE
C
C     CLASSICAL THERMAL DIFFUSION CHARGING RATE IN REGION III
      ARG3=-V*NUMBER
      IF(ABS(ARG3).GT.30.0) GO TO 7031
      RATE3=FACTOR*EXP(ARG3)*AFID
      GO TO 7032
 7031 RATE3=0.
 7032 CONTINUE
C
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C     CLASSICAL ELECTRIC FIELD CHARGING RATE IN REGION I
      IF(NUMBER-SCHARG)7008,7009,7009
 7008 RATE1=AFID*COEFF*(1.-NUMBER/SCHARG)**2
      GO TO 7010
 7009 RATE1=0.
 7010 CONTINUE
      RATE=RATE1+RATE2+RATE3
  818 RETURN
      END
      SUBROUTINE ZERO (C1,C0,RZERO)
C     TO CALCULATE RZERO FOR A GIVEN THETA
      B=(C0/C1)*SQRT(27./C1)
      CALL ARCCOS(B,1.,C)
      D=-2.*SQRT(C1/3.)
      RZERO=D*COS((C+6.28318)/3.)
      RETURN
      END
      SUBROUTINE ARCCOS(A,B,RCOS)
      RATIO=A/B
      T=1.
      SUM=0.
      TERM=RATIO
    1 U=2.*T-1.
      V=2.*T
      W=2.*T+1.
      TERM=TERM/V*U**2/W*RATIO**2
      SUM=SUM+TERM
      T=T+1.
      IF(TERM-5.E-05)3,3,1
    3 RCOS=1.5707963-SUM-RATIO
      RETURN
      END
      SUBROUTINE CHGSUM
      REAL LINC,LTHICK,JPART,JION
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK15/NPRINT,NSECT,SLNGTH,A,VO,TC,B,AC,WL,CL,CD,ET,SY,
     1VGAS,P,VIS,W,LINC,XPI,RIOVR,EPLT,AFID,XCD,ZMD,ZWT,
     2WT,LTHICK,JPART,JION,I,ROVRI
      COMMON/BLK20/SCHARG,CHRFID,TIMEI,TIMEF,V,FACTRE,RSIZE,CNUMBR,J,II,
     1ITER,OLDQF(20),OLDQT(20),SOLDQF(20),SOLDQT(20)
      IF(NVI.EQ.1) GO TO 50
      IF((I.EQ.1).AND.(II.EQ.1)) GO TO 51
      GO TO 52
   51 CONTINUE
      OLDQF(J)=0.
      OLDQT(J)=0.
   52 CONTINUE
      IF(ITER.NE.1) GO TO 53
      IF(II.GT.1) GO TO 50
      SOLDQF(J)=OLDQF(J)
      SOLDQT(J)=OLDQT(J)
   53 CONTINUE
      IF((ITER.GT.1).AND.(II.EQ.1)) GO TO 54
      GO TO 55
   54 CONTINUE
      OLDQF(J)=SOLDQF(J)
      OLDQT(J)=SOLDQT(J)
   55 CONTINUE
   50 CONTINUE
      IF(NVI.EQ.2) GO TO 56
      IF(I.GT.1) GO TO 56
      OLDQF(J)=0.
      OLDQT(J)=0.
   56 CONTINUE
      SATCHG=E*SCHARG
      IF(OLDQF(J).GE.SATCHG) GO TO 1
      CF1=((CHRFID*U*E)/(4.*EPSO))*(TIMEF-TIMEI)
      CF2=1./(1.-OLDQF(J)/SATCHG)
      QF=SATCHG*((CF1+CF2-1.)/(CF1+CF2))
      IF(QF.GT.SATCHG) QF=SATCHG
      GO TO 2
    1 CONTINUE
      QF=OLDQF(J)
    2 CONTINUE
      OLDQF(J)=QF
      ARG=(V*OLDQT(J))/E
      IF(ARG.GT.30.) GO TO 10
      QT=E/V*ALOG(E**2/BC/EPSO*RSIZE*VAVC*CHRFID/TDK/4.*(TIMEF-
     1TIMEI)+EXP(ARG))
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      OLDQT(J)=QT
      GO TO 9
   10 CONTINUE
      QT=OLDQT(J)
    9 CONTINUE
      CNUMBR=(QF+QT)/E
      RETURN
      END
      SUBROUTINE PRTINC
      REAL LINC,LTHICK,JPART,JION
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK15/NPRINT,NSECT,SLNGTH,A,VO,TC,B,AC,WL,CL,CD,ET,SY,
     1VGAS,P,VIS,W,LINC,XPI,RIOVR,EPLT,AFID,XCD,ZMD,ZWT,
     2WT,LTHICK,JPART,JION,I,ROVRI
      COMMON/BLK17/NREAD,NPRNT
      IF(NPRINT.NE.1) GO TO 8439
      IF(NSECT.GT.1) GO TO 1585
      WRITE(NPRNT,6550)
 6550 FORMAT(//' INCREMENTAL ANALYSIS OF PRECIPITATOR PERFORMANCE'//)
      WRITE(NPRNT,3010) ITL
 3010 FORMAT('0',40A2/)
 1585 CONTINUE
      NPRINT=0
      WRITE(NPRNT,7820) NSECT
 7820 FORMAT(///' CALCULATION IS IN SECTION NO. =',I2/)
      WRITE(NPRNT,7715)SLNGTH,TDK,VO
 7715 FORMAT(' SECTION LENGTH',F11.4,' M',16X,'GAS TEMPERATURE',F10.2
     1,' K',18X,'APPLIED VOLTAGE',1PE13.3,' V')
      WRITE(NPRNT,7716)LINC,P,TC
 7716 FORMAT(' LENGTH INCREMENT',F9.4,' M',16X,'GAS PRESSURE',6X,F5.2
     1,' ATM',18X,'TOTAL CURRENT',1PE15.3,' A')
      WRITE(NPRNT,7717)A,VIS,CD
 7717 FORMAT(' COLLECTION AREA',1PE14.4,' M2',11X,'GAS VISCOSITY',E15.3
     1,' KG/M*S',10X,'CURRENT DENSITY',E13.3,' A/M2')
      WTW=2.0*SY
      WRITE(NPRNT,7718)WTW,VG,CL
 7718 FORMAT(' WIRE-TO-WIRE',6X,F7.4,' M',16X,'GAS VOLUME FLOW',1PE13.3
     1,' M3/S',12X,'WIRE CURRENT/M',E14.3,' A/M')
      WRITE(NPRNT,7719)B,VGAS,ET
 7719 FORMAT(' WIRE-TO-PLATE',5X,F7.4,' M',16X,'GAS LINEAR FLOW',1PE13.3
     1,' M/S',13X,'DUST LAYER FIELD',E12.3,' V/M')
      WSEC=DL-ZWT+WT
      XPEN=100.-XPI
      WRITE(NPRNT,7720)WSEC,U,XPEN
 7720 FORMAT(' INCOMING DUST',5X,1PE11.4,' KG/M3',8X,'ION MOBILITY',6X
     1,E10.3,' M2/V*S',10X,'EST. INCR. PEN.',0PF9.2,' %')
      IF(NVI.EQ.1) GO TO 4689
      WRITE(NPRNT,4322)
 4322 FORMAT(///' INCREMENT   RIOVR    E AVERAGE   E PLATE   REDUCED FID
     1  J TOTAL    DUST MMD    DUST KG/M3    DUST LAYER    J DUST',6X,'J ION
     2S'/'    NUMBER',16X,'V/M',8X,'V/M',7X,'IONS/M3',5X,'NA/CM2',5X
     3,'REMOVED',4X,'REMOVED',5X,'MM/MINUTE',5X,'A/M2',8X,'A/M2'/)
      GO TO 4690
 4689 CONTINUE
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      WRITE(NPRNT,4333)
 4333 FORMAT(//' INCREMENT   ROVRI    E AVERAGE   E PLATE   REDUCED FID
     1  J TOTAL   DUST MMD   DUST KG/M3   DUST LAYER   J DUST',6X,'J ION
     2S'/'   NUMBER',16X,'V/M',8X,'V/M',7X,'IONS/M3',5X,'NA/CM2',5X
     3,'REMOVED',4X,'REMOVED',5X,'MM/MINUTE',5X,'A/M2',8X,'A/M2'/)
 4690 CONTINUE
 8439 CONTINUE
      IF(NVI.EQ.1) GO TO 4691
      WRITE(NPRNT,4323) I,RIOVR,ERAVG,EPLT,AFID,XCD,ZMD,WT,LTHICK,
     1JPART,JION
 4323 FORMAT(1X,4X,I2,5X,F6.3,2X,1PE11.3,1X,E11.4,1X,E11.4,1X,0PF7.1,3X,
     11PE10.2,2X,E11.3,1X,E11.3,1X,E10.2,2X,E10.2)
      GO TO 3000
 4691 CONTINUE
      WRITE(NPRNT,4323)I,ROVRI,ERAVG,EPLT,AFID,XCD,ZMD,WT,LTHICK,
     1JPART,JION
 3000 CONTINUE
      RETURN
      END
      SUBROUTINE PRTCHG
      REAL NWS
      INTEGER VISKIP,VISAME
      DIMENSION YY(20)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK4/NS
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      COMMON/BLK7/XDC(99,20)
      COMMON/BLK8/EAVG(30),CHFID(30)
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK16/NCALC,NI,VRATIO,NF
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP,
     2PATHL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
C
C OUTPUT FROM CHARGING ROUTINE
C
      WRITE(NPRNT,9992)
 9992 FORMAT(1H1)
      WRITE(NPRNT,356)
  356 FORMAT(/1X,'CHARGING RATES FOR PARTICLE SIZES FROM SUBROUTINE CHAR
     1GN OR CHGSUM'/)
      IF((NCALC.EQ.1).OR.(NEST.EQ.2)) GO TO 1880
      GO TO 1881
 1880 CONTINUE
      WRITE(NPRNT,1882)
 1882 FORMAT(/1X,'SUM OF CLASSICAL FIELD AND DIFFUSIONAL CHARGES USED FO
     1R PARTICLE CHARGING')
 1881 CONTINUE
      WRITE(NPRNT,2500)
 2500 FORMAT(//1X,'INCREMENT NO.',T20,'Q/QSATF FOR INDICATED PARTICLE SI
     1ZES')
      JS=1
      KS=8
 6544 CONTINUE
      IF(KS-NS) 6541,6542,6542
 6542 CONTINUE
      KS=NS
 6541 CONTINUE
      WRITE(NPRNT,357) (DIAM(J),J=JS,KS)
 357  FORMAT(//T7,10(E11.4,2X)//)
      WRITE(NPRNT,433)
  433 FORMAT(1X)
      DO 360 I=1,NF
      DO 359 J=JS,KS
      IF(NVI.EQ.1) GO TO 4692
      N = NI/2
      QSATM=(4.*PI*EPS0*(RAD(J)+TMFP)**2)*EAVG(N)*(1.+2.*((EPS-1.)/
     1(EPS+2.))*(RAD(J)/(RAD(J)+TMFP))**3)*VRATIO
      YY(J)=XDC(I,J)/QSATM
      GO TO 359
 4692 CONTINUE
      YY(J)=XDC(I,J)/QSAT(J)
  359 CONTINUE
      WRITE(NPRNT,358) I,(YY(J),J=JS,KS)
 358  FORMAT(T3,I2,T9,10(F7.4,6X))
  360 CONTINUE
      IF(KS.EQ.NS) GO TO 6543
      JS=JS+8
      KS=KS+8
      GO TO 6544
 6543 CONTINUE
      WRITE(NPRNT,9992)
      WRITE(NPRNT,432)
  432 FORMAT(/1X,'CHARGE ACCUMULATED ON PARTICLE SIZES IN EACH INCREMENT
     1'//1X,'INCREMENT',T20,'CHARGE FOR INDICATED PARTICLE SIZES')
      JS=1
      KS=8
 6565 CONTINUE
      IF(KS-NS) 6566,6567,6567
 6567 CONTINUE
      KS=NS
 6566 CONTINUE
      WRITE(NPRNT,425) (DIAM(J),J=JS,KS)
 425  FORMAT(//T8,10(E11.4,3X)//)
      WRITE(NPRNT,433)
      DO 431 I=1,NF
      WRITE(NPRNT,430) I,(XDC(I,J),J=JS,KS)
 430  FORMAT(T3,I2,T6,10(E13.5,1X))
 431  CONTINUE
      IF(KS.EQ.NS) GO TO 6568
      JS=JS+8
      KS=KS+8
      GO TO 6565
 6568 CONTINUE
      RETURN
      END
      SUBROUTINE WADJST (DIAM,I,WY,ONO,PXS,ATOTAL,VG,EFESR)
C                                       *******************************************
C                                       *                                         *
C                                       *  CORRECTION FACTORS IN THIS SUBROUTINE  *
C                                       *                                         *
C                                       *  ARE BASED ON DATA TAKEN UNDER          *
C                                       *                                         *
C                                       *  E.P.R.I. SPONSORSHIP BY SO.R.I.        *
C                                       *                                         *
C                                       *******************************************
      DOUBLE PRECISION EFESR
      DIMENSION DIAM(20),ONO(20),PXS(20),CFACT(24),DCHECK(24)
      DATA CFACT/2.43,2.325,2.24,2.17,2.11,2.05,2.00,1.965,1.92,1.885,1.
     185,1.82,1.79,1.76,1.74,1.71,1.685,1.5,1.37,1.27,1.18,1.115,1.05,1.
     200/
      DATA DCHECK/.2E-06,.25E-06,.3E-06,.35E-06,.4E-06,.45E-06,.5E-06,.5
     15E-06,.6E-06,.65E-06,.7E-06,.75E-06,.8E-06,.85E-06,.9E-06,.95E-06,
     21.E-06,1.5E-06,2.E-06,2.5E-06,3.E-06,3.5E-06,4.E-06,4.5E-06/
      IF(DIAM(I).GE.4.5E-06) GO TO 6
      IF(DIAM(I).LT.2.0E-07)GO TO 7
      DO 3 L=1,23
      IF((DIAM(I).GE.DCHECK(L)).AND.(DIAM(I).LE.DCHECK(L+1))) GO TO 4
      GO TO 3
    4 CONTINUE
      WFACT=CFACT(L)-((DIAM(I)-DCHECK(L))/(DCHECK(L+1)-DCHECK(L)))*
     1(CFACT(L)-CFACT(L+1))
      WY=WY*WFACT
      EFESR=1.-EXP(-(ATOTAL*WY)/(100.*VG))
      PXS(I)=EFESR*ONO(I)
      GO TO 5
    3 CONTINUE
    7 WY=WY*2.43
    6 CONTINUE
      EFESR=1.-EXP(-(ATOTAL*WY)/(100.*VG))
      PXS(I)=EFESR*ONO(I)
    5 CONTINUE
      RETURN
      END
      SUBROUTINE LNDIST (D50,SIGMAP,PRCU,PCNT)
      DIMENSION Y(100),Z(100),AREA(20),PRCU(21),PCNT(20)
      COMMON/BLK4/NS
      COMMON/BLK11/ENDPT(21),NENDPT
      PI=3.1416
      SIGMAZ=ALOG(SIGMAP)
      N=NS+2
      NINC=100
      ASUM=0.
      K=0
      DO 240 J=1,N
      IF(J.EQ.1)GO TO 230
      IF(J.EQ.(N))GO TO 232
      X2=ALOG(ENDPT(J))
      X1=ALOG(ENDPT(J-1))
      GO TO 233
230   CONTINUE
      X1=ALOG(0.01)
      X2=ALOG(ENDPT(J))
      GO TO 233
232   CONTINUE
      X1=ALOG(ENDPT(J-1))
      X2=ALOG(1000.)
233   CONTINUE
      DX=(X2-X1)/99.
      D=X1
      SGT1=1./(SIGMAZ*(2.*PI)**.5)
      SGT2=2.*SIGMAZ**2
      DO 234 I=1,NINC
      ARGY=-(D-ALOG(D50))**2/SGT2
      IF(ARGY.LT.-85.)ARGY=-85.
      Y(I)=SGT1*EXP(ARGY)
      D=D+DX
234   CONTINUE
      CALL QTFE(DX,Y,Z,NINC)
      ASUM=ASUM+Z(NINC)
      IF(J.LT.N) PRCU(J)=ASUM
      IF((J.EQ.1).OR.(J.EQ.N))GO TO 240
      K=K+1
      AREA(K)=Z(NINC)
240   CONTINUE
      DO 241 I=1,NS
      PCNT(I)=AREA(I)/ASUM
241   CONTINUE
      SUM=0.
      DO 2 I=1,NS
      SUM=SUM+PCNT(I)
2     CONTINUE
      CHECK1 = 1.0 - SUM
      PCNT(NS)=PCNT(NS)+CHECK1
      CHECK2 = 1.0 - PRCU(NENDPT)
      PRCU(NENDPT)=PRCU(NENDPT)+CHECK2
      RETURN
      END
      SUBROUTINE QTFE (DX,Y,Z,NINC)
      DIMENSION Y(100),Z(100)
      SUM2=0.
      IF(NINC - 1) 4,3,1
1     DDX=.5*DX
C
C     INTEGRATION LOOP
      DO2 I=2,NINC
      SUM1=SUM2
      SUM2=SUM2+DDX*(Y(I)+Y(I-1))
2     Z(I-1)=SUM1
3     Z(NINC)=SUM2
4     RETURN
      END
      SUBROUTINE LNFIT (PRCU,D50,SIGMAP,GFIT)
C     THIS SUBROUTINE FITS CUMPERCENT CURVE TO A LOGNORMAL DISTRIBUTION
      DIMENSION Z(21),Y(21),PRCU(21)
      COMMON/BLK11/ENDPT(21),NENDPT
      NSTAG=0
      J=0
      DO 1 I=1,NENDPT
      IF(PRCU(I).LE.0.0)GO TO 1
      J=J+1
      Z(J)=ALOG(ENDPT(I))
      IF(PRCU(I).GE.99.0) GO TO 4
      IF(PRCU(I).GT.50.)GO TO 3
      XY=PRCU(I)/100.
    2 XYY=SQRT(ALOG(1.0/XY**2))
      Y(J)=XYY-((2.515517+0.802853*XYY+0.010328*XYY**2)/(1.0+1.432788*X
     1YY+0.189269*XYY**2+0.001308*XYY**3))
      IF(PRCU(I).GT.50.)GO TO 5
      Y(J)=-Y(J)
      GO TO 5
    3 XY=1.0-(PRCU(I)/100.)
      GO TO 2
    5 NSTAG=NSTAG+1
    1 CONTINUE
C     CALL CURVE FIT ROUTINE
    4 CALL CFIT(A,B,GFIT,NSTAG,Z,Y)
C     CALCULATE D50 AND SIGMAP
      D50=EXP(-A/B)
      SIGMAP=EXP(1.0/B)
      RETURN
      END
      SUBROUTINE CFIT (A,B,R,NSTAG,Z,Y)
C     THIS SUBROUTINE FITS A STRAIGHT LINE, Y=A+BX, USING LEAST SQUARES
      DIMENSION Z(21),Y(21)
      XN=0.0
      SUMX=0.0
      SUMY=0.0
      SUMXY=0.0
      SUMXX=0.0
      SUMYY=0.0
      DO 6 I=1,NSTAG
      SUMX=SUMX+Z(I)
      SUMY=SUMY+Y(I)
      SUMXY=SUMXY+Z(I)*Y(I)
      SUMXX=SUMXX+Z(I)**2
      SUMYY=SUMYY+Y(I)**2
      XN=XN+1.0
6     CONTINUE
C     CALCULATE A,B
      B=(XN*SUMXY-SUMX*SUMY)/(XN*SUMXX-SUMX**2)
      A=(SUMXX*SUMY-SUMX*SUMXY)/(XN*SUMXX-SUMX**2)
      R=SQRT(B*((XN*SUMXY-SUMX*SUMY)/(XN*SUMYY-SUMY**2)))
      RETURN
      END
      SUBROUTINE PRTSUM
      REAL LINCS
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK18/SCOREF,CZMDL,CSIGMO,NRUN,SNUCK,ZIGGY,RMMD,RSIGMA
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP,
     2PATHL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
      COMMON/OPACTY/CMR(10),CMI(10),UPTOLM(10),NTIMES,NCOMP,NNCOMP
     1,DELTAD(20),DMDLD(20),RDMDLD(20),CDMDLD(20),TOTOPA(2),TOTNRP(2)
      SCA=ATOTAL/VG
      SCAE=SCA*5.08
      VOSUM=0.
      ACD=0.
      IRJ=0
      RHOCGS=RHO*100.
      DO 6571 I=1,NUMSEC
      VOSUM=VOS(I)*FLOAT(LSECT(I))*LINCS(I)+VOSUM
      CD=(TCS(I)/AS(I))*1.E+05*FLOAT(LSECT(I))*LINCS(I)/PL
      IF(MODL.NE.1)CD=CD/9.3E-02
      IF(RHOCGS*CD.GT.1.5E+13)IRJ=1
      ACD=CD+ACD
 6571 CONTINUE
      AVO=VOSUM/PL/1000.
      PEN=100.-SCOREF
      WRITE(NPRNT,1994)
 1994 FORMAT(1H1)
      WRITE(NPRNT,9110)
 9110 FORMAT(9X,'*******************************************************
     1******************************************************************
      *************************************************************')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
 1060 FORMAT(9X,'*',114X,'*')
      WRITE(NPRNT,9501)
 9500 FORMAT(9X,'*',42X,'SUMMARY TABLE OF ESP OPERATING',42X,'*'/9X,'*'
     1,44X,'PARAMETERS AND PERFORMANCE',44X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9500)
 9501 FORMAT(9X,'*',49X,'E.P.A. ESP MODEL',49X,'*'/9X,'*',43X,
     1'I.E.R.L.-R.T.P. AND SO.R.I.',44X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      IF(IRJ.EQ.1)WRITE(NPRNT,9513)
 9513 FORMAT(9X,'*',16X,'WARNING MESSAGE:'
     1,11X,'THE ELECTRIC FIELD IN THE ASH LAYER HAS EXCEEDED 15 KV/CM.'
     2,13X,'*'/9X,'*',43X,'THE CURRENT DENSITY SPECIFIED IN THE INPUT '
     3,'DATA MAY BE',17X,'*'/9X,'*',43X,'UNREALISTICALLY HIGH FOR THE'
     4,' SPECIFIED FLY ASH RESISTIVITY.',12X,'*'/9X,'*',43X,'THE '
     5,'INTERNAL DATA SET MAY BE USED TO ESTIMATE ELECTRICAL ',14X,'*'
     6/9X,'*',43X,'OPERATING POINTS.',54X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9502) NDSET
9502 FORMAT(9X,'*',47X,'DATA SET NUMBER ',I3,48X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9512) NRUN
9512 FORMAT(9X,'*',40X,'NON-IDEAL CONDITION SET NUMBER',I3,41X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      IF(SCOREF.GT.99.90)WRITE(NPRNT,9514)PEN,SCOREF
      IF(SCOREF.GT.99.00.AND.SCOREF.LE.99.90)WRITE(NPRNT,9515)PEN,SCOREF
      IF(SCOREF.LE.99.00)WRITE(NPRNT,9516)PEN,SCOREF
9514 FORMAT(9X,'*',16X,'ESP PERFORMANCE:',11X,'PENETRATION =',F8.3
     1,' %',48X,'*'/9X,'*',114X,'*'/9X,'*',43X,'EFFICIENCY  =',F8.3,' %'
     2,48X,'*')
9515 FORMAT(9X,'*',16X,'ESP PERFORMANCE:',11X,'PENETRATION =',F7.2
     1,' %',49X,'*'/9X,'*',114X,'*'/9X,'*',43X,'EFFICIENCY  =',F7.2,' %'
     2,49X,'*')
9516 FORMAT(9X,'*',16X,'ESP PERFORMANCE:',11X,'PENETRATION =',F6.1
     1,' %',50X,'*'/9X,'*',114X,'*'/9X,'*',43X,'EFFICIENCY  =',F6.1,' %'
     2,50X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9517)SCA,SCAE
9517 FORMAT(9X,'*',43X,'SCA',9X,'=',F6,1,' M2/(M3/SEC)',2X,'='
     1F5.0,1X,'FT2/(1000 ACFM)',16X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9518)AVO,ACD
9518 FORMAT(9X,'*',16X,'ELECTRICAL CONDITIONS:     AVG. APPLIED VOLTAGE
     1 =',F6.1,' KV',40X,'*'/9X,'*',114X,'*'/9X,'*',43X,'AVG. CURRENT '
     2,'DENSITY =',F6.1,' NA/CM2',36X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9520)RHOCGS
9520 FORMAT(9X,'*',43X,'FLY ASH RESISTIVITY  =',1PE10.1,' OHM-CM',32X,
     1'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9521)ZMMDI,SIGMI
9521 FORMAT(9X,'*',16X,'SIZE DISTRIBUTIONS:',8X,'INLET MMD  ='
     1,F5.1,' UM    INLET SIGMAP  =',F5.1,27X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9522)CZMDL,CSIGMO
9522 FORMAT(9X,'*',43X,'OUTLET MMD =',F5.1,' UM    '
     1,'OUTLET SIGMAP =',F5.1,27X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9523)SNUCK,RMMD
 9523 FORMAT(9X,'*',16X,'NON-IDEAL CONDITIONS:',6X,'GAS SNEAKAGE FRACTIO
     1N =',F5.2,4X,'RAPPING MMD    =',F5.1,' UM',15X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9524)ZIGGY,RSIGMA
 9524 FORMAT(9X,'*',43X,'GAS VELOCITY SIGMAG   =',F5.2,'    RAPPING SIGM
     1AP =',F5.1,18X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      IF(PATHL.EQ.0)GO TO 2000
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9511)TOTOPA(1),PATHL,TOTNRP(1)
 9511 FORMAT(9X,'*',16X,'VISIBLE EMISSIONS:',9X,'OPACITY',11X,'=',F5.1
     1,' %',45X,'*'/9X,'*',114X,'*'/9X,'*',43X,'STACK DIAMETER    ='
     2,F5.1,' M',45X,'*'/9X,'*',114X,'*'/9X,'*',43X,
     3'EXTINCTION COEFF. =',F7.3,' 1/M',41X,'*')
      WRITE(NPRNT,1060)
 2000 WRITE(NPRNT,1060)
      WRITE(NPRNT,9110)
      RETURN
      END
      SUBROUTINE CMAW (VW,NX,NY,SX,SY,PI,AC,NWIRE)
C    COOPERMAN SERIES DETERMINATION FOR VOLTAGE WIRE TO PLATE
C    FOR SUBROUTINE EFIELD
      REAL NUM,M,NWIRE
      COMMON/BLK13/VCOOP(15,15),ICYC,NSCT,ICOOP,VSTR(15,15,99)
      NX1=NX-1
      NY1=NY-1
      DO 402 I=1,NX
      DO 430 J=1,NY
      X=FLOAT(I-1)*SX/FLOAT(NX1)
      Y=FLOAT(J-1)*SY/FLOAT(NY1)
      IF(X.EQ.0..AND.Y.EQ.0.)GO TO 440
      GO TO 450
  440 VCOOP(I,J)=VW
      GO TO 430
  450 CONTINUE
      M=-NWIRE
      NUM=0.0
      DENOM=0.0
  490 E1=PI*(Y-(2.*M*SY))/(2.*SX)
      F1=PI*X/(2.*SX)
      G1=PI*M*SY/SX
      H1=PI*AC/(2.*SX)
      E2=(EXP(E1)+EXP(-E1))/2.
      F2=COS(F1)
      G2=(EXP(G1)+EXP(-G1))/2.
      H2=COS(H1)
      TT=(E2-F2)/(E2+F2)
      TB=(G2-H2)/(G2+H2)
      F=ALOG(TT)
      G=ALOG(TB)
      NUM=NUM+F
      DENOM=DENOM+G
      IF(M.LT.NWIRE) GO TO 408
      GO TO 410
  408 M=M+1.0
      GO TO 490
  410 VCOOP(I,J)=VW*NUM/DENOM
  430 CONTINUE
  402 CONTINUE
      RETURN
      END
      SUBROUTINE MIE(C1,C4,X,A1,E1,E2,R1,R2,R3)                         OPAC
      R1=0.0
      R3=0.0
      S1=0.0
      S2=0.0
      S3=0.0
      S4=0.0
      C2=COS(A1)
      S=(SIN(A1))**2
      T=1.2*X+9.
      X1=X*C1
      X2=X*C4
      C=X1/((X1**2)+(X2*.2))
      C3=-X2/((X1**2)+(X2**2))
      Z2=0.5*(EXP(X2)-EXP(-X2))
      Z3=0.5*(EXP(X2)+EXP(-X2))
      Z4=SIN(X1)*Z3
      Z5=COS(X1)*Z2
      Z6=(C*SIN(X1)*Z3)-(C3*COS(X1)*Z2)-(COS(X1)*Z3)
      Z7=C*COS(X1)*Z2+C3*SIN(X1)*Z3+SIN(X1)*Z2
      A=-C+((Z4*Z6+Z5*Z7)/(Z6**2+Z7**2))
      A7=((Z5*Z6-Z4*Z7)/(Z6**2+Z7**2))-C3
      Y=SIN(X)
      Z=COS(X)
      W4=Y
      W5=Z
      W2=Y/X-Z
      W3=Z/X+Y
      P1=0.0
      P=1.0
      T2=0.
      T1=C2
      R4=1.0
  660 C=((A*C1+A7*C4)/(C1**2+C4**2))+(R4/X)
      C3=(A7*C1-A*C4)/(C1**2+C4**2)
      A4=C*W2-W4
      A5=C3*W2
      A6=C*W2-C3*W3-W4
      A8=C3*W2+C*W3-W5
      A2=(A4*A6+A5*A8)/(A6**2+A8**2)
      A3=(A5*A6-A4*A8)/(A6**2+A8**2)
      C=A*C1-A7*C4+R4/X
      C3=A7*C1+A*C4
      B4=C*W2-W4
      B5=C3*W2
      B6=C*W2-C3*W3-W4
      B8=C3*W2+C*W3-W5
      B2=(B4*B6+B5*B8)/(B6**2+B8**2)
      B3=(B5*B6-B4*B8)/(B6**2+B8**2)
      R5=R4+R4+1.
      R6=R5/(R4*(R4+1.))
      S1=R6*(A2*P+B2*T1)+S1
      S3=R6*(A3*P+B3*T1)+S3
      S2=R6*(B2*P+A2*T1)+S2
      S4=R6*(B3*P+A3*T1)+S4
      R3=R3+R5*(A2+B2)
      IF(A2.LT.1.0E-18)A2=1.0E-18
      IF(A3.LT.1.0E-18)A3=1.0E-18
      IF(B2.LT.1.0E-18)B2=1.0E-18
      IF(B3.LT.1.0E-18)B3=1.0E-18
      B = A2**2+A3**2+B2**2+B3**2
  897 R1=R1+R5*B
      R6=R4
      R4=R4+1.0
      P2=P1
      P1=P
      P=(R5/R6)*P1*C2-(R4/R6)*P2
      T3=T2
      T2=T1
      T1=C2*(P-P2)-R5*S*P1+T3
      W6=W4
      W7=W5
      W4=W2
      W5=W3
      W2=(R5/X)*W4-W6
      W3=(R5/X)*W5-W7
      C=(R4*X1)/(X1**2+X2**2)
      C3=(-R4*X2)/(X1**2+X2**2)
      C5=C-A
      C6=C3-A7
      A=-C+(C5/(C5**2+C6**2))
      A7=-C3-(C6/(C5**2+C6**2))
      D1=1.0E-14
      IF(B.LT.D1) GO TO 921
      IF(R4.LE.T) GO TO 860
  921 R5=2./(X*X)
      R1=R1*R5
      R3=R3*R5
      R2=R3-R1
      E1=S1**2+S3**2
      E2=S2**2+S4**2
      RETURN
      END
      SUBROUTINE ARAOPT(NODES,D,FD,TOTARA,TTOPAR,OFD)                   OPAC
      REAL LAMDA(10),NRMCST
      DIMENSION DELMDA(10),FLAMDA(10),D(20),FD(20)
      DIMENSION OFD(20),QARRAY(20,20)
      COMMON/OPACTY/CMR(10),CMI(10),UPTOLM(10),NTIMES,NCOMP,NNCOMP
     1,DELTAD(20),DMDLD(20),RDMDLD(20),CDMDLD(20),TOTOPA(2),TOTNRP(2)
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP,
     2PATHL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
      DATA LAMDA/.43,.46,.49,.52,.55,.58,.61,.64,.67,.7/
      DATA FLAMDA/0.10835,0.56043,1.94282,6.63173,9.29377,
     18.12621,4.69826,1.63458,0.29890,0.03830/
      DATA DELMDA/10*0.03/,ANG/0.0/,PI/3.141956/
      IF(NWAVES-1)100,100,101
100   LAMDA(1)=0.55
      FLAMDA(1)=1.
      DELMDA(1)=1.
101   NRMCST=0.
      DO 601 I=1,NODES
      QBR=0.
      JJ=NCOMP*NLAMDA
      JJJ=(NCOMP-1)*NLAMDA+1
      DO 501 J=1,NWAVES
      ALPHA=PI*D(I)/LAMDA(J)
      JLMDAC=(NCOMP-1)*NWAVES+J
      IF(NLAMDA.LT.2)GO TO 549
      DO 550 JC=JJJ,JJ
      IF(LAMDA(J)-UPTOLM(JC))551,550,550
550   CONTINUE
551   JJJ=JC
      GO TO 552
549   JC=NCOMP
552   IF(NTIMES.GT.1 .OR. NNCOMP.GT.0)GO TO 510
      CALL MIE(CMR(JC),CMI(JC),ALPHA,ANG,AIL,EIR,QS,QA,Q)
      QARRAY(JLMDAC,I)=Q
510   Q=QARRAY(JLMDAC,I)
      QBR=QBR+Q*FLAMDA(J)*DELMDA(J)
501   CONTINUE
      OFD(I)=FD(I)*QBR
      NRMCST=NRMCST+OFD(I)*DELTAD(I)
601   CONTINUE
      TTOPAR=NRMCST*TOTARA
      DO 602 I=1,NODES
      OFD(I)=OFD(I)/NRMCST*TTOPAR
602   CONTINUE
999   CONTINUE
      RETURN
      END
      SUBROUTINE MASARA(DENSTY,NOXES,X,FX,DELTAX,TOTMAS,TOTARA)         OPAC
      REAL NRMCST,NRMCSM
      DIMENSION X(20),FX(20),DELTAX(20)
      NRMCSM=0.0
      NRMCST=0.0
      DO 100 NX=1,NOXES
      NRMCSM=NRMCSM+FX(NX)*DELTAX(NX)
      FX(NX)=FX(NX)/X(NX)
      NRMCST=NRMCST+FX(NX)*DELTAX(NX)
100   CONTINUE
      IF(ABS(NRMCSM-1.)-0.001)200,200,300
200   TOTARA=TOTMAS/DENSTY*3./2.*NRMCST
      GO TO 350
300   TOTARA=1./DENSTY*3./2.*NRMCST
350   CONTINUE
      DO 400 NX=1,NOXES
      FX(NX)=FX(NX)/NRMCST
400   CONTINUE
      RETURN
      END
      SUBROUTINE ADJUST
C                            *********************************************
C                            *                                           *
C                            *                                           *
C                            *  RAPPING REENTRAINMENT PROCEDURE IN       *
C                            *                                           *
C                            *  THIS SUBROUTINE WAS DEVELOPED UNDER      *
C                            *                                           *
C                            *  THE SPONSORSHIP OF E.P.R.I. BY SO.R.I.   *
C                            *                                           *
C                            *********************************************
      DOUBLE PRECISION EFESR,DLOG,EFFWR
      REAL LINCS
      DIMENSION RPCNT(20),PRCUC(21),WUNCOR(20),EUNCOR(20),
     1PCTOT(20),CPCTOT(20),WSL(20),PXS(20),PRCUNR(21),RPRCU(21)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK4/NS
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      COMMON/BLK11/ENDPT(21),NENDPT
      COMMON/BLK12/ARD50(10),ARSIGM(10),ASNUCK(15),AZNUMS(15),AZIGGY(15)
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK18/SCOREF,CZMDL,CSIGMO,NRUN,SNUCK,ZIGGY,RMMD,RSIGMA
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP,
     2PATHL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
      COMMON/OPACTY/CMR(10),CMI(10),UPTOLM(10),NTIMES,NCOMP,NNCOMP
     1,DELTAD(20),DMDLD(20),RDMDLD(20),CDMDLD(20),TOTOPA(2),TOTNRP(2)
      NRUN = 0
      NS1=NS+1
      NUMS1=NUMSEC-1
      CONVF=3.67E+03*(TDK/PS(NUMSEC))
      NRAPDC=0
      X=0.0
      DO 1550 I=1,NUMSEC
 1550 IF(MODL.NE.1)LINCS(I)=LINCS(I)*0.305
      DO 1555 I=1,NS
      EFESR=DXS(I)/ONO(I)
      IF(EFESR.GT.0.999999) EFESR=0.999999
      X=X+EFESR*PCNT(I)
 1555 CONTINUE
 1713 CONTINUE
      NRAPDC=NRAPDC+1
      IF(NRAPDC.EQ.1) GO TO 6078
      GO TO 6080
 6078 CONTINUE
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      ARD50(1)=6.0
      ARSIGM(1)=2.5
      RMMD=6.0
      RSIGMA=2.5
      GO TO 6079
 6080 CONTINUE
      RMMD=ARD50(NRAPDC)
      RSIGMA=ARSIGM(NRAPDC)
 6079 CONTINUE
      CALL LNDIST(RMMD,RSIGMA,RPRCU,RPCNT)
      DO 7575 I=1,NS
      RPCNT(I)=RPCNT(I)*1.E+02
 7575 CONTINUE
      NONCK=0
 1867 CONTINUE
      NONCK=NONCK+1
      SNUCK=ASNUCK(NONCK)
      ZIGGY=AZIGGY(NONCK)
      ZNUMS=AZNUMS(NONCK)
      WRITE(NPRNT,18)
   18 FORMAT(1H1//' PARTICLE SIZE RANGE STATISTICS'/)
      WRITE(NPRNT,1868) NONCK
 1868 FORMAT(/' CORRECTIONS FOR NON-IDEAL CONDITIONS USING SET NO.',I3
     1,' OF CORRECTION PARAMETERS'/)
C
C        PRINT DIAM., PERCENT, AND EFFICIENCY FOR EACH SIZE RANGE
C
      WRITE(NPRNT,19)
   19 FORMAT('    PARTICLE    CCF    INLET %   OUTLET %     CORRECTED
     1 NO-RAP      NO-RAP      NO-RAP   CORRECTED   CORRECTED    CORRECT
     2ED'/'   DIAMETER',10X,'IN BAND    IN BAND      OUTLET %    EFFICIE
     3NCY   MIG. VEL.     PEN.   EFFICIENCY   MIG. VEL.   PENETRATION'/)
C
C
      Y=0.0
      DO 2990 I=1,NS
      II=I
      EFESR=DXS(I)/ONO(I)
      IF (EFESR .GT..999999 ) EFESR = .999999
      XEP=EFESR*100.DO
      IF (XEP .GE. 99.9999  ) XEP = 99.9999
      IF(EFESR.GE.0.99999)WY=XMV(I)*100.
      IF(EFESR.LT.0.99999)WY=(VG/ATOTAL)*100.*ALOG(100./(100.-XEP))
      IF(ZIGGY-0.0)4704,4704,4705
 4704 F1=1.
      GO TO 4706
 4705 CONTINUE
      F1=1.+.766*EFESR*ZIGGY**1.786+.0755*ZIGGY*DLOG(1.DO/(1.DO-EFESR))
 4706 CONTINUE
      IF(SNUCK-0.0)4701,4701,4702
 4701 F2=1.
      GO TO 4703
 4702 F2=DLOG(1.-EFESR)/(ZNUMS*DLOG(SNUCK+(1.-SNUCK)*(1.0-EFESR)**(1./
     1ZNUMS)))
 4703 CONTINUE
      WYS=WY/F2
      WYV=WY/F1
      ZNLFF = F1*F2
      WYSV=WY/ZNLFF
      WUNCOR(I)=WY
      EUNCOR(I)=EFESR*100.
      CALL WADJST(DIAM,II,WYSV,ONO,PXS,ATOTAL,VG,EFESR)
      IF (EFESR .GT..999999 ) EFESR = .999999
      XEP=EFESR*100.DO
      IF (XEP .GE. 99.9999  ) XEP = 99.9999
      IF(EFESR.GE.0.99999)WY=XMV(I)*100.
      IF(EFESR.LT.0.99999)WY=(VG/ATOTAL)*100.*ALOG(100./(100.-XEP))
      PXS(I)=EFESR*ONO(I)
      Y = Y + EFESR * PCNT(I)
 2990 CONTINUE
      IDC=0
      SPO=0.
      SCPO=0.
      IX=0
 1341 CONTINUE
      SCOREF = 0.0
      IDC=IDC+1
      DO 3540 I=1,NS
      IX=IX+1
      EFESR=PXS(I)/ONO(I)
      IF (EFESR .GT..999999 ) EFESR = .999999
      XEP=EFESR*100.DO
      IF (XEP .GE. 99.9999  ) XEP = 99.9999
      IF(EFESR.GE.0.99999)WY=XMV(I)*100.
      IF(EFESR.LT.0.99999)WY=(VG/ATOTAL)*100.*ALOG(100./(100.-XEP))
      XY=PCNT(I)*100.
      PENTR=100.-XEP
      PCTOT(I)=PENTR*PCNT(I)*1.E-02
      IF(IX.GT.1) GO TO 7130
      CLPTLS=0.
      DO 1 IS=1,NUMS1
      CLPTLS=CLPTLS+FLOAT(LSECT(IS))*LINCS(IS)
    1 CONTINUE
      NYX=0
 1430 CONTINUE
      NYX=NYX+1
      IF(NYX.EQ.2) GO TO 1431
      XEFF=Y
      IF(NEFF.EQ.2) XEFF=X
      EXPONT=ALOG(1./(1.-XEFF))
      XMELS=DL*EXP(-(EXPONT*CLPTLS)/PL)
      XMCLS=XMELS*(1.-EXP(-(EXPONT*FLOAT(LSECT(NUMSEC))*LINCS(NUMSEC))
     1/PL))
      XMLLS=XMELS-XMCLS
      XMCLS=XMCLS*CONVF
      IF(NTEMP.EQ.1) RAPLOS=0.155*XMCLS**0.905
      IF(NTEMP.EQ.2) RAPLOS=0.618*XMCLS**0.894
      GO TO 1432
 1431 CONTINUE
      EXPONT=ALOG(1./(1.-Y))
      YMELS=DL*EXP(-(EXPONT*CLPTLS)/PL)
      YMCLS=YMELS*(1.-EXP(-(EXPONT*FLOAT(LSECT(NUMSEC))*LINCS(NUMSEC))
     1/PL))
      YMLLS=YMELS-YMCLS
      YMCLS=YMCLS*CONVF
 1432 CONTINUE
      IF(NYX.EQ.1) GO TO 1430
 7130 CONTINUE
      RNS=((RAPLOS/(DD*CONVF))*RPCNT(I)*1.E-02)/((3.14159*DIAM(I)**3)/6.
     1)
      WYSV=WY
      EFFWR=(ONO(I)*(1.-EXP(-(ATOTAL*WYSV)/(100.*VG)))-RNS)/ONO(I)
      CRNP = ONO(I)*(1.-EXP(-(ATOTAL*WYSV)/(100.*VG)))- RNS
      IF(CRNP.LE.0.0) EFFWR = EFESR
      IF(EFFWR.GT..999999) EFFWR=.999999
      COREFF=EFFWR*100.D0
      IF(COREFF.GE.99.9999) COREFF=99.9999
      IF(EFFWR.GE.0.99999) WYP=WYSV
      IF(EFFWR.LT.0.99999) WYP=(VG/ATOTAL)*100.*ALOG(100./(100.-COREFF))
      SCOREF = SCOREF + COREFF*PCNT(I)
      CPENTR=100.-COREFF
      CPCTOT(I)=CPENTR*PCNT(I)*1.E-02
      IF(IDC.NE.1) GO TO 1343
      SPO=SPO+PCTOT(I)
      SCPO=SCPO+CPCTOT(I)
 1343 CONTINUE
      SL=(1.0-EFESR)*ONO(I)
      WSL(I)=SL*(1.33333*3.14159*RAD(I)**3)*DD
      IF(IDC.EQ.1) GO TO 1344
      PCTOT(I)=(PCTOT(I)/SPO)*100.
      CPCTOT(I)=(CPCTOT(I)/SCPO)*100.
      DLD=ALOG10(ENDPT(I+1))-ALOG10(ENDPT(I))
      DELTAD(I)=DLD
      DMDLD(I)=(PCTOT(I)*YMLLS*CONVF*1.E-02)/DLD
      RDMDLD(I)=(RPCNT(I)*RAPLOS*1.E-02)/DLD
      CDMDLD(I)=DMDLD(I)+RDMDLD(I)
      WRITE(NPRNT,2291) DIAM(I),CCF(I),XY,PCTOT(I),CPCTOT(I),XEP,WY,
     1PENTR,COREFF,WYP,CPENTR
 2291 FORMAT(1X,1PE10.3,2X,0PF6.3,3X,F6.3,4X,F7.4,7X,F7.4,5X,F8.4,5X,F7.
     13,3X,F8.4,3X,F8.4,5X,F7.3,6X,F8.4)
 1344 CONTINUE
 3540 CONTINUE
      IF(IDC.EQ.1) GO TO 1341
C
      Y=Y*100.
      X = X * 100.
      WRITE(NPRNT,2292) ETAO,X
 2292 FORMAT(///' EFFICIENCIES FOR CONVERGENCE CHECK:  STATED OR PREVIOUS
     1 CALCULATION = ',F7.3,'   FINAL CALCULATION = ',F7.3)
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      X=X/100.
      WRITE(NPRNT,5802) ZMMDI
 5802 FORMAT(//5X,'MMD OF INLET SIZE DISTRIBUTION    =',F6.2)
      WRITE(NPRNT,5803) SIGMI
 5803 FORMAT(5X,'SIGMAP OF INLET SIZE DISTRIBUTION =',F6.2)
      IF(NDIST.EQ.1) WRITE(NPRNT,9250) GFIT
 9250 FORMAT(5X,'QUALITY OF LOG-NORMAL FIT = ',F5.3)
      PRCUC(1)=0.
      SUMC=PRCUC(1)
      DO 1751 I=1,NS
      SUMC=SUMC+CPCTOT(I)
      PRCUC(I+1)=SUMC
 1751 CONTINUE
      CALL LNFIT(PRCUC,CZMDL,CSIGMO,CGFIT)
      WRITE(NPRNT,4615) ZIGGY,SNUCK,ZNUMS
 4615 FORMAT(5X,'GAS VELOCITY SIGMAG =',F5.2/5X,'SNEAKAGE FRACTION   ='
     1,F5.2/5X,'NO. BAFFLED STAGES  =',F3.0)
      WRITE(NPRNT,7900) NTEMP
 7900 FORMAT(5X,'NTEMP =',I2)
      WRITE(NPRNT,7901) RMMD
 7901 FORMAT(5X,'RAPPING MMD   =',F6.2)
      WRITE(NPRNT,7902) RSIGMA
 7902 FORMAT(5X,'RAPPING SIGMA =',F6.2)
      WRITE(NPRNT,3675)Y
 3675 FORMAT(//5X,'ADJUSTED NO-RAP EFF. = ',F8.4)
C
      PRCUNR(1)=0.
      SUMNR=PRCUNR(1)
      DO 1750 I=1,NS
      SUMNR=SUMNR+PCTOT(I)
      PRCUNR(I+1)=SUMNR
 1750 CONTINUE
      CALL LNFIT(PRCUNR,ZMDL,SIGMO,ZGFIT)
 2982 WRITE(NPRNT,2997) ZMDL
 2997 FORMAT(5X,'MMD OF EFFLUENT UNDER NO-RAP CONDITIONS    =',F5.2)
      WRITE(NPRNT,5801) SIGMO
 5801 FORMAT(5X,'SIGMAP OF EFFLUENT UNDER NO-RAP CONDITIONS =',F5.2)
      WRITE(NPRNT,9250) ZGFIT
      COREFW=(VG/ATOTAL)*100.*ALOG(100./(100.-SCOREF))
      WZ=(VG/ATOTAL)*100.*ALOG(100./(100.-Y))
      WRITE(NPRNT,2998) WZ
 2998 FORMAT(5X,'PRECIPITATION RATE PARAMETER UNDER NO-RAP CONDITIONS ='
     1,F7.3//)
      WRITE(NPRNT,5002) SCOREF
 5002 FORMAT(5X,'EFF. CORRECTED FOR RAPPING = ',F8.4)
      WRITE(NPRNT,8352) CZMDL
 8352 FORMAT(5X,'CORRECTED MMD OF EFFLUENT    =',F5.2)
      WRITE(NPRNT,5800) CSIGMO
 5800 FORMAT(5X,'CORRECTED SIGMAP OF EFFLUENT =',F5.2)
      WRITE(NPRNT,9250) CGFIT
      WRITE(NPRNT,5003) COREFW
 5003 FORMAT(5X,'CORRECTED PRECIPITATION RATE PARAMETER =',F8.2)
      WRITE(NPRNT,6565)
 6565 FORMAT(1H1//' UNADJUSTED MIGRATION VELOCITIES AND EFFICIENCIES, AN
     1D DISCRETE OUTLET MASS LOADINGS'//)
      WRITE(NPRNT,1980)
 1980 FORMAT(2X,8HPARTICLE,4X,16HIDEAL UNADJUSTED,4X,16HIDEAL UNADJUSTED
     1,5X,6HNO-RAP,6X,12HRAPPING PUFF,4X,15HNO-RAP+RAP PUFF,4X,12HRAPPIN
     2G PUFF)
      WRITE(NPRNT,1981)
 1981 FORMAT(4X,'DIAM.',10X,9HMIG. VEL.,10X,10HEFFICIENCY,6X,8HDM/DLOGD,
     17X,'DM/DLOGD',9X,8HDM/DLOGD,8X,12HDISTRIBUTION/ 5X,'(M)',11X
     28H(CM/SEC),14X,3H(%),10X,9H(MG/DSCM),6X,9H(MG/DSCM),8X,9H(MG/DSCM)
     311X,3H(%)/)
      DO 1982 M=1,NS
      WRITE(NPRNT,1983) DIAM(M),WUNCOR(M),EUNCOR(M),DMDLD(M),RDMDLD(M),
     1CDMDLD(M),RPCNT(M)
 1983 FORMAT(1X,1PE10.3,6X,1PE10.3,9X,1PE10.3,7X,1PE10.3,5X,1PE10.3,7X,
     11PE10.3,8X,1PE10.3)
 1982 CONTINUE
      IF(PATHL.NE.0.0) CALL  OPAC(RAPLOS,YMLLS,CONVF)                      OPAC
2000  NRUN = NRUN + 1
      CALL PRTSUM
      NTIMES=NTIMES+1
      IF(NONCK.LT.NONID) GO TO 1867
      IF(NRAPDC.LT.NRAPD) GO TO 1713
      DO 1560 I=1,NUMSEC
 1560 IF(MODL.NE.1)LINCS(I)=LINCS(I)/0.305
      RETURN
      END
      SUBROUTINE OPAC(RAPLOS,YMLLS,CONVF)
      DIMENSION YTONRP(2),OFDDMD(20,2),OFDRMD(20,2),RTONRP(2)
      DIMENSION OFDTOT(20,2),YTOSPE(2),RTOSPE(2),TOTSPE(2),
     1YTONRK(2),RTONRK(2),TOTNRK(2),YTOOPA(2),RTOOPA(2)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK4/NS
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP,
     2PATHL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
      COMMON/OPACTY/CMR(10),CMI(10),UPTOLM(10),NTIMES,NCOMP,NNCOMP
     1,DELTAD(20),DMDLD(20),RDMDLD(20),CDMDLD(20),TOTOPA(2),TOTNRP(2)
2     FORMAT(5X,'ERROR MESSAGE: THE PRESENT SIZE OF ARRAYS DOES NOT',
     1' PERMIT OPACITY CALCULATIONS FOR MORE THAN 10 COMPOSITIONS.',/,
     25X,'CALCULATIONS HAVE BEEN PERFORMED FOR THE FIRST 10 PUT IN.')
3     FORMAT(5X,'ERROR MESSAGE: TO PUT IN MORE THAN TWO COMPOSITIONS',
     1' FOR OPACITY, NWAVES MUST BE SET TO 1.',/,
     25X,'CALCULATIONS HAVE BEEN PERFORMED WITH YOUR FIRST TWO ',
     3'REFRACTIVE INDICES.')
4     FORMAT(5X,'ERROR MESSAGE: TO USE A REFRACTIVE INDEX THAT VARIES',
     1' OVER WAVELENGTH THE PROGRAM CANNOT PRESENTLY ACCOMMODATE MORE',
     2' THAN TWO COMPOSITIONS.',/,
     35X,'YOUR FIRST TWO COMPOSITIONS HAVE BEEN UTILIZED.')
      DC 2045 M=1,NS
      DIAM(M)=DIAM(M)*1.0E+06
      DMDLD(M)=DMDLD(M)/CONVF*1000.
      RDMDLD(M)=RDMDLD(M)/CONVF*1000.
 2045 CDMDLD(M)=CDMDLD(M)/CONVF*1000.
2055  RAPLOS=RAPLOS/CONVF*1000.
      YMLLS=YMLLS*1000.
      IF(NTIMES-1)2040,2040,2010
2040  IF(NCOMPS)2009,2009,2002
2002  IF(NLAMDA)2020,2020,2030
2020  IF(NWAVES-1)2013,2012,2013
2012  IF(NCOMPS-10)2014,2014,2015
2015  NCOMPS=10
      WRITE(NPRNT,2)
      GO TO 2014
2013  IF(NCOMPS-2)2016,2016,2017
2017  NCOMPS=2
      WRITE(NPRNT,3)
2016  NWAVES=10
2014  NLAMDA=1
      READ(NREAD,2001)(CMR(I),CMI(I),I=1,NCOMPS)
2001  FORMAT(12(F5.3))
      GO TO 2010
2030  NWAVES=10
      JJ=1
      M=NLAMDA
      IF(NCOMPS-2)2018,2018,2019
2019  NCOMPS=2
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      WRITE(NPRNT,4)
 2018 DO 2035 I=1,NCOMPS
      READ(NREAD,2001)(CMR(J),CMI(J),UPTOLM(J),J=JJ,M)
      JJ=M+1
      M=M+NLAMDA
 2035 CONTINUE
      GO TO 2010
 2009 NCOMPS=2
      IF(NWAVES-1)2022,2011,2022
 2022 NWAVES=10
 2011 NLAMDA=1
 2010 CONTINUE
      DD=DD*0.001
      YVLLS=YMLLS/DD
      VAPLOS=RAPLOS/DD
      TOTMAS=YMLLS+RAPLOS
      TOTVOL=TOTMAS/DD
      CALL MASARA(DD,NS,DIAM,DMDLD,DELTAD,YMLLS,YOTARA)
      CALL MASARA(DD,NS,DIAM,RDMDLD,DELTAD,RAPLOS,ROTARA)
      NCOMP=1
      JJ=NLAMDA
      J=1
  2600 M=0
      IF(NRAP.EQ.3)GO TO 2460
      IF(NOPRNT.NE.0) GO TO 2601
      WRITE(NPRNT,30)
    30 FORMAT(1H1)
 2601 WRITE(NPRNT,5)PATHL,YMLLS,RAPLOS,TOTMAS,YVLLS,VAPLOS,TOTVOL,DD
 5    FORMAT(1H0,50X,'VISIBLE EMISSION PARAMETERS',///,36X,'LIGHT BEAM P
     1ATHLENGTH OR STACK DIAMETER = L = ',1PE10.3,' METERS',/,
     213X,'OUTLET PARTICULATE MASS LOADING = W = ',1PE10.3,'(NO-RAP), ',
     31PE10.3,'(RAPPING PUFFS), AND ',1PE10.3,'(TOTAL) GM/M**3',/,
     411X,'OUTLET PARTICULATE VOLUME LOADING = V = ',1PE10.3,
     5'(NO-RAP), ',
     61PE10.3,'(RAPPING PUFFS), AND ',1PE10.3,'(TOTAL) CM**3/M**3',/,
     743X,'PARTICLE DENSITY = P = ',1PE10.3,' GM/CM**3',/)
 2460 M=M+1
      NNCOMP=0
      CALL ARAOPT(NS,DIAM,DMDLD,YOTARA,YTONRP(M),OFDDMD(1,M))
      NNCOMP=1
      CALL ARAOPT(NS,DIAM,RDMDLD,ROTARA,RTONRP(M),OFDRMD(1,M))
      DO 2620 I=1,NS
      OFDTOT(I,M)=OFDDMD(I,M)+OFDRMD(I,M)
 2620 CONTINUE
      TOTNRP(M)=YTONRP(M)+RTONRP(M)
      YTOSPE(M)=YTONRP(M)/YMLLS
      RTOSPE(M)=RTONRP(M)/RAPLOS
      TOTSPE(M)=TOTNRP(M)/TOTMAS
      YTONRK(M)=1./DD/YTOSPE(M)
      RTONRK(M)=1./DD/RTOSPE(M)
      TOTNRK(M)=1./DD/TOTSPE(M)
      YTOOPA(M)=(1.-EXP(-YTONRP(M)*PATHL))*100.
      RTOOPA(M)=(1.-EXP(-RTONRP(M)*PATHL))*100.
      TOTOPA(M)=(1.-EXP(-TOTNRP(M)*PATHL))*100.
      IF(M-2)2459,2461,2461
 2459 IF(NCOMP.EQ.NCOMPS)GO TO 2462
      NCOMP=NCOMP+1
      GO TO 2460
2461  NCOMPP=NCOMP-1
      IF(NOPRNT.NE.0)GO TO 2502
2463  WRITE(NPRNT,7)NCOMPP,NCOMP
6     FORMAT(21X,'COMPOSITION #',I2,/)
7     FORMAT(21X,'COMPOSITION #',I2,60X,'COMPOSITION #',I2,/)
2464  WRITE(NPRNT,8)
8     FORMAT(8X,'NO-RAP',8X,'RAPPING PUFFS',3X,'NO-RAP+RAP PUFFS',
     18X,'PARTICLE',
     25X,8X,'NO-RAP',8X,'RAPPING PUFFS',3X,'NO-RAP+RAP PUFFS',/,
     31X,3(4X,'DE/DLOGD(1/M)'),10X,'DIA.(UM)',
     45X,3(4X,'DE/DLOGD(1/M)'))
      DO 2500 I=1,NS
      WRITE(NPRNT,9)OFDDMD(I,1),OFDRMD(I,1),OFDTOT(I,1),DIAM(I),
     1OFDDMD(I,2),OFDRMD(I,2),OFDTOT(I,2)
9     FORMAT(6X,1PE10.3,2(7X,1PE10.3),2(10X,1PE10.3),2(7X,1PE10.3))
2500  CONTINUE
      WRITE(NPRNT,14)YTONRP(1),RTONRP(1),TOTNRP(1),
     1YTONRP(2),RTONRP(2),TOTNRP(2)
14    FORMAT(/,2X,'E = ',2(1PE10.3,7X),1PE10.3,
     1'----------- M**(-1) ----------',2(1PE10.3,7X),1PE10.3)
      WRITE(NPRNT,15)YTOSPE(1),RTOSPE(1),TOTSPE(1),
     1YTOSPE(2),RTOSPE(2),TOTSPE(2)
15    FORMAT(2X,'SPE=',2(1PE10.3,7X),1PE10.3,
     1'----------- M**2/GM ----------',2(1PE10.3,7X),1PE10.3)
      WRITE(NPRNT,16)YTONRK(1),RTONRK(1),TOTNRK(1),
     1YTONRK(2),RTONRK(2),TOTNRK(2)
16    FORMAT(2X,'K = ',2(1PE10.3,7X),1PE10.3,
     1'---------- CM**3/M**2 --------',2(1PE10.3,7X),1PE10.3)
 2502 WRITE(NPRNT,20)YTOOPA(1),RTOOPA(1),TOTOPA(1),
     1YTOOPA(2),RTOOPA(2),TOTOPA(2)
20    FORMAT(/,2X,'OP= ',2(1PE10.3,7X),1PE10.3,
     1'-------------- % -------------',2(1PE10.3,7X),1PE10.3)
      NCOPPP=NCOMPP
 2607 IF(NRAP.EQ.3)GO TO 2605
      WRITE(NPRNT,17)NCOPPP,(CMR(I),CMI(I),I=J,JJ)
      IF(NLAMDA-1)2605,2605,2606
2606  WRITE(NPRNT,22)(UPTOLM(I),I=J,JJ)
2605  J=JJ+1
      JJ=JJ+NLAMDA
      NCOPPP=NCOPPP+1
      IF(NCOPPP-NCOMP)2607,2607,2608
2608  CONTINUE
17    FORMAT(/,3X,'FOR COMPOSITION #',I2,' REFRACTIVE INDEX =',
     110(F4.2,F6.3,'I,'))
22    FORMAT(12X,'UP TO WAVELENGTH(MICRONS) =',10(3X,F5.3,4X))
      GO TO 2609
 2462 IF(NOPRNT.NE.0)GO TO 2503
      WRITE(NPRNT,6)NCOMP
      WRITE(NPRNT,10)
10    FORMAT(8X,'NO-RAP',7X,'RAPPING PUFFS',2X,'NO-RAP+RAP PUFFS',
     18X,'PARTICLE',/,
     21X,3(4X,'DE/DLOGD(1/M)'),10X,'DIA.(UM)')
      DO 2501 I=1,NS
      WRITE(NPRNT,9)OFDDMD(I,1),OFDRMD(I,1),OFDTOT(I,1),DIAM(I)
2501  CONTINUE
      WRITE(NPRNT,11)YTONRP(1),RTONRP(1),TOTNRP(1)
11    FORMAT(2X,'E = ',2(1PE10.3,7X),1PE10.3,'----------- M**(-1)')
      WRITE(NPRNT,12)YTOSPE(1),RTOSPE(1),TOTSPE(1)
12    FORMAT(2X,'SPE=',2(1PE10.3,7X),1PE10.3,'----------- M**2/GM')
      WRITE(NPRNT,13)YTONRK(1),RTONRK(1),TOTNRK(1)
13    FORMAT(2X,'K = ',2(1PE10.3,7X),1PE10.3,'---------- CM**3/M**2')
 2503 WRITE(NPRNT,21)YTOOPA(1),RTOOPA(1),TOTOPA(1)
21    FORMAT(/,2X,'OP= ',2(1PE10.3,7X),1PE10.3,'-------------- %')
      WRITE(NPRNT,17)NCOMPS,(CMR(I),CMI(I),I=J,JJ)
      IF(NLAMDA-1)2609,2609,2610
2610  WRITE(NPRNT,22)(UPTOLM(I),I=J,JJ)
2609  IF(NOPRNT.NE.0)GO TO 2611
      WRITE(NPRNT,23)
23    FORMAT(/,4X,'E  = EXTINCTION COEFFICIENT (M**2/M**3)',35X,'OP = ',
     1'OPACITY = 1 - EXP(-EL)',/,3X,'SPE = SPECIFIC MASS EXTINCTION',
     2' COEFFICIENT (M**2/GM)',28X,'OPACITY = 1 - EXP(-(SPE)WL)',/,
     34X,'K  = SPECIFIC PARTICULATE VOLUME (CM**3/M**2)',34X,
     4'OPACITY = 1 - EXP(-WL/PK) = 1 - EXP(-VL/K)',//,5X,'DE/DLOGD',
     5' = DIFFERENTIAL EXTINCTION COEFFICIENT (1/M) OR DISTRIBUTION',
     6' OF OPTICAL EXTINCTION OVER PARTICLE SIZE;',/,
     711X,'E = SUMMATION OF (DE/DLOGD)*DLOGD')
 2611 NCOMP=NCOMP+1
      IF(NCOMP.LE.NCOMPS)GO TO 2600
      DD=DD*1000.
      DO 2645 I=1,NS
      DIAM(I)=DIAM(I)*1.0E-06
2645  CONTINUE
      RETURN
      END
      SUBROUTINE RAPPE                                                  RAP
      REAL LAYER,NWS,LINCS
      INTEGER VISKIP,VISAME
      INTEGER RAPI,RAPSEC
      DIMENSION PRCBL(21),APCT(21),PMASS(21)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK4/NS
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      COMMON/BLK11/ENDPT(21),NENDPT
      COMMON/BLK12/ARD50(10),ARSIGM(10),ASNUCK(15),AZNUMS(15),AZIGGY(15)
      COMMON/BLK16/NCALC,NI,VRATIO,NF
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP,
     2PATHL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
      COMMON/BLK23/BOLFRC(15,5),BOLTIM(15),REMMD(15,5),LBOIL,NUMBOL
     $ ,RESIG(5),PUFMAS,OLDPEN,CYCPEN
      COMMON/BLK24/RAPI,MAPRAP(45),TIMER,LAYER(45),DDRAP,
     $ RAPLAY(45),PCNTR(21),SMASS(21),TSMASS,AVGPEN,ACCPEN,OLDTIM,LREEN
     $ ,ZXNO(20),REPCT,CPMASS(20)
      COMMON/BLK25/RAPDST(45,20),NREEN,THICK(99),TINC,LOOPR,DMDLS(20)
      COMMON/OPACTY/CMR(10),CMI(10),UPTOLM(10),NTIMES,NCOMP,NNCOMP
     1,DELTAD(20),DMDLD(20),RDMDLD(20),CDMDLD(20),TOTOPA(2),TOTNRP(2)
      SNUCK=ASNUCK(1)
      ZIGGY=AZIGGY(1)
      ZNUMS=AZNUMS(1)
      CONVF=3670.*TDK/PS(NUMSEC)
      IF(NREEN.NE.0) GO TO 100
      IF(LREEN.EQ.0) OLDTIM = 0.
      IF(LREEN.EQ.0) ACCPEN = 0.
      IF(LREEN.EQ.0) OLDPEN = 0.
      IF(LOOPR.EQ.0) NTIMES = 1
      READ(NREAD,1000) TIMRAP,(MAPRAP(I),I=1,45),REPCT,NUMBOL,NDAT
      IF(TIMRAP.EQ.0.) GO TO 290
      IF(NDAT.EQ.0) GO TO 98
      DO 95 J=1,NUMSEC
   95 READ(NREAD,1002) (BOLFRC(I,J),I=1,NUMBOL)
      DO 96 J=1,NUMSEC
   96 READ(NREAD,1002) (REMMD(I,J),I=1,NUMBOL),RESIG(J)
      READ(NREAD,1002) (BOLTIM(I), I=1,NUMBOL),DDRAP
 1002 FORMAT(13F6.3)
 1000 FORMAT(F10.5,45I1, F8.5,I2,I5)
      WRITE(NPRNT,2000)(MAPRAP(I),I=1,45),TIMRAP,REPCT
 2000 FORMAT(//' RAP INCREMENTS ',45I1,'  AT TIME',F8.2,'  MIN'//' ',
     $ F9.7,'  DUST REENTRAINED WITH PROFILE = '//' NORMALIZED CURVE: ')
      DO 90 J=1,NUMSEC
   90 WRITE(NPRNT,2003)(BOLFRC(I,J),I=1,NUMBOL)
 2003 FORMAT(' ',18X,8F10.3)
      WRITE(NPRNT,2004)
 2004 FORMAT('0WITH MMD:')
      DO 91 J=1,NUMSEC
   91 WRITE(NPRNT,2003)(REMMD(I,J),I=1,NUMBOL),RESIG(J)
      WRITE(NPRNT,2005)(BOLTIM(I),I=1,NUMBOL)
      WRITE(NPRNT,2006)DDRAP
 2005 FORMAT('0DURATION IN SEC:  ',7F10.3)
 2006 FORMAT(/' RAPPING PUFF PARTICLE DENSITY:  ',F6.0)
      GO TO 97
   98 WRITE(NPRNT,2002)(MAPRAP(I),I=1,45),TIMRAP,REPCT
 2002 FORMAT(//' RAP INCREMENTS ',45I1,'  AT TIME',F8.2,'  MIN WITH THE
     $SAME PROFILE @ ',F10.7)
   97 CONTINUE
      TIMER = TIMRAP
      RAPI = 0
  100 CONTINUE
      DTIMER = (TIMER - OLDTIM) * 60.
      OLDTIM = TIMER
      IF(NRAP.EQ.3) GO TO 101
      WRITE(NPRNT,2010) TIMER,DTIMER
 2010 FORMAT(///' THE TIME IS',F8.3,2X,'MIN     THE TIME INTERVAL IS ',
     $ F8.2,' SEC')
      GO TO 102
  101 IF(NREEN.EQ.0) WRITE(NPRNT,2011) TIMER
      IF(LBOIL.EQ.NUMBOL+1)WRITE(NPRNT,2011) TIMER
 2011 FORMAT(//' THE TIME IS',F8.3,'  MIN')
  102 CONTINUE
      IF(NRAP.EQ.1) WRITE(NPRNT,2001)
 2001 FORMAT(//'    DIAMETER UM',7X,
     $ 'INPUT %',3X,'INPUT DMDLD',6X,'OUTPUT %',2X,'OUTPUT DMDLD',4X,
     $ 'EFFICIENCY',3X,'PENETRATION',5X,'PEN MASS',2X,'MASS DUE RAP'/)
C CALC OUTPUT INFORMATION BLOCK
      DDR = DDRAP
      IF(NREEN.EQ.0) DDR = DD
      IF(NREEN.EQ.0) TSMASS = 0.
      TPMASS = 0.
      TOMASS = 0.
      DO 110 J = 1,NS
C NON IDEAL CORRECTIONS
      PENJ = XNO(J)/ONO(J)
      IF(PENJ.LT.0.000001)PENJ = 0.000001
      AWYJ = VG/ATOTAL*100.*ALOG(1./PENJ)
      IF(PENJ.LT.0.00001)AWYJ = XMV(J)*100.
      IF(SNUCK.NE.0.)GO TO 410
      IF(ZIGGY.EQ.0.)GO TO 420
  410 CONTINUE
      AWYJ = AWYJ/(1.+.0755*ZIGGY*ALOG(1./PENJ)+.766*(1.-PENJ)*ZIGGY**
     $ 1.786)/(ALOG(PENJ)/ZNUMS/ALOG(SNUCK+(1.-SNUCK)*PENJ**(1./ZNUMS)))
  420 CONTINUE
```

```
      IF(DIAM(J).GE.0.0000044)GO TO 430
      AWYJ = AWYJ*(-4.668-.46*ALOG(DIAM(J)))
  430 CONTINUE
      PENJ = EXP(-ATOTAL/VG/100.*AWYJ)
      IF(PENJ.LT.0.000001)PENJ=0.000001
      XNO(J) = ONO(J)*PENJ
C
      IF(NREEN.EQ.0.AND.LREEN.EQ.0) ZXNO(J) = XNO(J)
      XNO(J) = XNO(J) + RAPDST(NF+1,J)
      PMASS(J) = (ZXNO(J)*DD+(XNO(J)-ZXNO(J))*DDR)*4./3.*3.14159*RAD(J)
     $ **3*VG
      IF(NREEN.EQ.0.AND.LREEN.EQ.0)CPMASS(J) = 0.
      CPMASS(J) = CPMASS(J) + PMASS(J)*DTIMER
  110 TPMASS = TPMASS + PMASS(J)
C CALC OUTPUT STATISTICS
      DO 120 J = 1,NS
      DIA = DIAM(J)*1.E+06
      PCTIN = PCNT(J)*100.
      DLD = ALOG10(ENDPT(J+1))-ALOG10(ENDPT(J))
      DELTAD(J) = DLD
      DMDLDI = ONO(J)*4./3.*3.14159*RAD(J)**3*DD/DLD*CONVF
      PCTOUT = PMASS(J)/TPMASS*100.
      DMDLDO = XNO(J)*4./3.*3.14159*RAD(J)**3*DD/DLD*CONVF
      IF(NREEN.EQ.0)DMDLS(J)=DMDLDO
      DMDLD(J) = DMDLS(J)
      CDMDLD(J) = DMDLDO
      RDMDLD(J) = CDMDLD(J)-DMDLD(J)
      OMASS = ONO(J)*4./3.*3.14159*RAD(J)**3*DD*VG
      PEN = PMASS(J)/OMASS*100.
      EFFIC = 100.-PEN
      TOMASS = TOMASS + OMASS
      IF(NREEN.NE.0) GO TO 115
      SMASS(J) = PMASS(J)
      TSMASS = TSMASS + SMASS(J)
  115 CONTINUE
      DMASS = PMASS(J) - SMASS(J)
      IF(NRAP.NE.1) GO TO 120
      WRITE(NPRNT,2020) DIA,PCTIN,DMDLDI,PCTOUT,DMDLDO,EFFIC,PEN,PMASS
     $ (J),DMASS
  120 CONTINUE
 2020 FORMAT(1H ,2F14.2,E14.3,F14.2,E14.3,2F14.4,E14.3,E14.3)
C CALC AVG OUTPUT STATISTICS
      PENE = TPMASS/TOMASS * 100.
      APCT(1) = 0.
      DO 130 J = 1,NS
  130 APCT(J+1) = APCT(J) + PMASS(J)/TPMASS*100.
      CALL LNFIT(APCT,D5W,SIGGO,GG)
      TDMASS = TPMASS - TSMASS
      YMLLS = TSMASS/VG
      RAPLOS = TDMASS/VG*1.0E+06
      ACCPEN = ACCPEN + TPMASS * DTIMER
      AVGPEN = ACCPEN /(TIMER*60.)
      IF(NREEN.EQ.0) PUFMAS = ACCPEN
      IF(NRAP.EQ.3) GO TO 131
      WRITE(NPRNT,2030) TPMASS,TSMASS,TDMASS,PENE,ACCPEN,AVGPEN,D5W,
     $ SIGGO,GG
 2030 FORMAT(  ' TOTAL PENETRATION MASS = ',E12.3,' KG/SEC WITH',E12.3,
     $ ' DUE STEADY STATE AND ',E12.3,' DUE RAPPING'/ ' INSTANTANEOUS PE
     $NETRATION = ',F9.2,' %'/ ' THE ACCUMULATED PENETRATION MASS IS ',
     $ E10.3, ' KG FOR AN AVG PENETRATION OF ',E10.3,' KG/SEC'/ ' OUTPUT
     $ MMD = ',E10.2,10X,'SIGMA = ',E10.2,10X,'QUALITY OF FIT = ',F8.3 )
      GO TO 132
  131 IF(NREEN.EQ.0)    WRITE (NPRNT,2031) PENE,TPMASS,ACCPEN,AVGPEN
      IF(LBOIL.EQ.NUMBOL+1)WRITE(NPRNT,2031)PENE,TPMASS,ACCPEN,AVGPEN
 2031 FORMAT(1H ,F7.2,' % PEN = ',E10.3,' KG/SEC FOR ',E10.3,' KG ACCUM
     $PEN AND ',E10.3,' KG/SEC AVG PEN')
  132 IF(NREEN.EQ.0)GO TO 134
      IF(PATHL.EQ.0.)GO TO 133                                          OPAC
      NOPRNT = 1                                                        OPAC
      CALL OPAC(RAPLOS,YMLLS,CONVF)                                     OPAC
      NTIMES = NTIMES+1                                                 OPAC
  133 GO TO 170
  134 CONTINUE
      IF(NRAP.EQ.3) GO TO 139
C WRITE THICKNESS
      NSEC = 1
      NSECC = LSECT(1)
      WRITE(NPRNT,2040)
 2040 FORMAT(///' THE THICKNESS OF THE DUST LAYER IS'//' ',13X,'SECTION'
     $ ,11X,'INCREMENT',11X,'THICKNESS IN MM')
  139 CONTINUE
      DO 140 I = 1,NF
      IF(LREEN.EQ.0) LAYER(I) = 0.
      LAYER(I) = LAYER(I) + THICK(I)*DTIMER/60.
      IF(NRAP.EQ.3) GO TO 140
      WRITE(NPRNT,2050) NSEC,I,LAYER(I)
 2050 FORMAT(1H ,10X,I10,10X,I10,10X,E10.3)
      IF(I.NE.NSECC) GO TO 140
      NSEC = NSEC +1
      NSECC = LSECT(NSEC) +NSECC
  140 RAPLAY(I) = 0.
C CALC RAP DUST
      DO 150 I=1,NF
      IF(MAPRAP(I).EQ.0) GO TO 150
      RAPLAY(I) = LAYER(I)
      LAYER(I) = 0.
  150 CONTINUE
      LBOIL = 1
      GO TO 190
  170 DO 180 I = 1,NF
  180 LAYER(I) = LAYER(I) + THICK(I)*DTIMER/60.
  190 CONTINUE
      IF (LBOIL.GT.NUMBOL) GO TO 250
      DO 249 I=1,NF
      NSEC = 1
      NSECC = LSECT(1)
      DO 245 K=1,NF
      IF(K.EQ.I) GO TO 246
      IF(K.NE.NSECC) GO TO 245
      NSEC = NSEC +1
      NSECC = LSECT(NSEC) +NSECC
  245 CONTINUE
  246 RAPSEC = NSEC
      IF(RAPSEC.EQ.RAPI) GO TO 247
      RAPI = RAPSEC
      IF(MAPRAP(I).EQ.0)GO TO 247
      CALL LNDIST(REMMD(LBOIL,RAPSEC),RESIG(RAPSEC),PRCBL,PCNTR)
  247 CONTINUE
      II = I+1
      CUNITS=25.4
      IF(MODL.EQ.1)CUNITS=1000.
      DO 248 J=1,NS
      RAPDST(II,J) = 0.
      IF(MAPRAP(I).EQ.0) GO TO 248
      RAPDST(II,J) = PCNTR(J)*RAPLAY(I)*AS(RAPSEC)/FLOAT(LSECT(
     $ RAPSEC))/(4./3.*3.14159*RAD(J)**3*BS(RAPSEC)*2.0*WLS(RAPSEC)/
     $ NWS(RAPSEC)*LINCS(RAPSEC)*CUNITS)*BOLFRC(LBOIL,RAPSEC)*REPCT
     $ *1000./DDRAP
  248 CONTINUE
  249 CONTINUE
      IF(NREEN.NE.0) GO TO 240
C CORRECT FOR TIME LAG
      NNF = 0.
      DO 228 I=1,NF
      J = NF-I+1
      IF(MAPRAP(J).NE.0) GO TO 229
  228 NNF = NNF +1
  229 CONTINUE
      TIMER = TIMER +TINC*FLOAT(NNF)/60.
      OLDTIM = TIMER
      ACCPEN = ACCPEN + TSMASS*TINC*FLOAT(NNF)
      DO 230 I = 1,NF
  230 LAYER(I) = LAYER(I) + THICK(I)*FLOAT(NNF)*TINC/60.
  240 TIMER = TIMER + BOLTIM(LBOIL)/60.
      LBOIL = LBOIL +1
      NREEN = 1
      LOOPR = 1
      GO TO 300
C WRITE THICKNESS
  250 LBOIL = 1
      PUFMAS = ACCPEN - PUFMAS
      CYCPEN = ACCPEN - OLDPEN
      IF(MAPRAP(NF).NE.0) OLDPEN = ACCPEN
      NSEC = 1
      NSECC = LSECT(1)
      IF(NRAP.EQ.3) GO TO 261
      WRITE(NPRNT,2040)
      DO 260 I = 1,NF
      WRITE(NPRNT,2050) NSEC,I,LAYER(I)
      IF(I.NE.NSECC) GO TO 260
      NSEC = NSEC +1
      NSECC = LSECT(NSEC) +NSECC
  260 CONTINUE
  261 PENE = AVGPEN/TOMASS*100.
      WRITE(NPRNT,2060)PENE,PUFMAS
 2060 FORMAT(//' END OF RAP'///' CUMULATIVE PENETRATION =',F8.2,' %'//
     $' TOTAL PENETRATION FOR THIS PUFF =',E10.3,' KG'//)
      IF(MAPRAP(NF).EQ.0)GO TO 266
      WRITE(NPRNT,2065)
 2065 FORMAT('0FINAL STATISTICS FOR THIS CYCLE'/'0DIAM UM   AVG PEN %')
      DO 265 J=1,NS
      DIA = DIAM(J)*1.0E+06
      CPEN = CPMASS(J)/(ONO(J)*3.1416*RAD(J)**3*DD*VG*TIMER)*1.25
  265 WRITE(NPRNT,2066)DIA,CPEN
 2066 FORMAT('  ',F6.2,5X,F7.3)
      WRITE(NPRNT,2070)CYCPEN,PENE
 2070 FORMAT(' TOTAL PENETRATION FOR THIS CYCLE = ',E10.3,' KG'//
     $ ,' AVERAGE PERCENT PENETRATION = ',F8.2,' %')
  266 CONTINUE
      NREEN = 0
      LREEN = 1
      NFN = NF+1
      DO 280 I=1,NFN
      DO 270 J = 1,NS
  270 RAPDST(I,J) = 0.
  280 CONTINUE
      GO TO 300
  290 LOOPR = 0
      IF(MAPRAP(1).NE.0)LOOPR = 1
      NREEN = 0
      LREEN = 0
  300 CONTINUE
      RETURN
      END
      SUBROUTINE CHEKIN                                                 CHEK
      REAL LINCS,NWS
      INTEGER VISKIP,VISAME
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      COMMON/BLK11/ENDPT(21),NENDPT
      COMMON/BLK12/ARD50(10),ARSIGM(10),ASNUCK(15),AZNUMS(15),AZIGGY(15)
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK16/NCALC,NI,VRATIO,NF
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP,
     2PATHL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
C     THE FOLLOWING STATEMENT DETERMINES WHERE THIS DATA IS PRINTED
      NNPRNT=NPRNT
      DLB=DL/2.29E-03
      PLB=PL/0.305
      RHOCGS=100.*RHO
      IF(NENDPT.LT.1.OR.NENDPT.GT.21)WRITE(NNPRNT,512)
  512 FORMAT('0***** NENDPT IS OUTSIDE ALLOWED RANGE')
      IF(NDATA.LT.1.OR.NDATA.GT.4)WRITE(NNPRNT,514)
  514 FORMAT('0***** NDATA IS OUTSIDE ALLOWED RANGE')
      IF(NRAP.LT.0.OR.NRAP.GT.3)WRITE(NNPRNT,516)
  516 FORMAT('0***** NRAP IS OUTSIDE ALLOWED RANGE')
      IF(PATHL.GT.20.)WRITE(NNPRNT,518)
  518 FORMAT('0>>>>> CHECK VALUE OF PATHL')
      GO TO (20,91,147,151),NDATA
   20 IF(NEST.LT.1.OR.NEST.GT.2)WRITE(NNPRNT,520)
  520 FORMAT('0***** NEST IS OUTSIDE ALLOWED RANGE')
      IF(NDIST.LT.1.OR.NDIST.GT.2)WRITE(NNPRNT,522)
  522 FORMAT('0***** NDIST IS OUTSIDE ALLOWED RANGE')
      IF(NVI.LT.1.OR.NVI.GT.2)WRITE(NNPRNT,524)
  524 FORMAT('0***** NVI IS OUTSIDE ALLOWED RANGE')
      IF(NX.LT.1.OR.NX.GT.15)WRITE(NNPRNT,526)
  526 FORMAT('0***** NX IS OUTSIDE ALLOWED RANGE')
      IF(NY.LT.1.OR.NY.GT.15)WRITE(NNPRNT,528)
  528 FORMAT('0***** NY IS OUTSIDE ALLOWED RANGE')
      IF(NITER.LT.1)WRITE(NNPRNT,530)
  530 FORMAT('0***** NITER IS OUTSIDE ALLOWED RANGE')
      IF(NVI.EQ.2.AND.NITER.GT.1)WRITE(NNPRNT,532)
  532 FORMAT('0>>>>> NITER SHOULD = 1 FOR NVI = 2')
      IF(NCALC.LT.0.OR.NCALC.GT.1)WRITE(NNPRNT,534)
  534 FORMAT('0***** NCALC IS OUTSIDE ALLOWED RANGE')
      IF(NRAPD.LT.1.OR.NRAPD.GT.10)WRITE(NNPRNT,536)
  536 FORMAT('0***** NRAPD IS OUTSIDE ALLOWED RANGE')
      IF(NEFF.LT.1.OR.NEFF.GT.2)WRITE(NNPRNT,538)
  538 FORMAT('0***** NEFF IS OUTSIDE ALLOWED RANGE')
      IF(NTEMP.LT.1.OR.NTEMP.GT.2)WRITE(NNPRNT,540)
  540 FORMAT('0***** NTEMP IS OUTSIDE ALLOWED RANGE')
      IF(NONID.LT.1.OR.NONID.GT.15)WRITE(NNPRNT,542)
  542 FORMAT('0***** NONID IS OUTSIDE ALLOWED RANGE')
      IF(NCALC.NE.0)GO TO 45
      IF(NN.LT.5.OR.NN.GT.10)WRITE(NNPRNT,544)
  544 FORMAT('0>>>>> NN IS OUTSIDE DESIRED RANGE')
   45 IF(NVI.EQ.1)GO TO 53
      IF(IFINAL.LT.10)WRITE(NNPRNT,546)
  546 FORMAT('0>>>>> CHECK VALUE OF IFINAL')
      IF(JI2.LE.JI1)WRITE(NNPRNT,548)
  548 FORMAT('0***** JI2 SHOULD BE > JI1')
      IF(VISKIP.LT.0.OR.VISKIP.GT.1)WRITE(NNPRNT,550)
  550 FORMAT('0***** VISKIP IS OUTSIDE ALLOWED RANGE')
      IF(VISAME.LT.1.OR.VISAME.GT.2)WRITE(NNPRNT,552)
  552 FORMAT('0***** VISAME IS OUTSIDE ALLOWED RANGE')
   53 IF(NDATA.NE.1)GO TO 73
      IF(MODL.EQ.1)GO TO 57
      IF(DLB.LT.0.1.OR.DLB.GT.10.)WRITE(NNPRNT,554)
  554 FORMAT('0>>>>> CHECK VALUE OF DL')
      IF(PLB.LT.10..OR.PLB.GT.100.)WRITE(NNPRNT,556)
  556 FORMAT('0>>>>> CHECK VALUE OF PL')
      GO TO 58
   57 IF(DL.LT.3.E-04.OR.DL.GT.3.E-02)WRITE(NNPRNT,554)
      IF(PL.LT.3..OR.PL.GT.30.)WRITE(NNPRNT,556)
   58 IF(ETAO.GT.100.)WRITE(NNPRNT,558)
  558 FORMAT('0>>>>> CHECK VALUE OF ETAO')
      IF(DD.LT.1000..OR.DD.GT.3000.)WRITE(NNPRNT,560)
  560 FORMAT('0>>>>> CHECK VALUE OF DD')
      IF(EPS.LT.1..OR.EPS.GT.100.)WRITE(NNPRNT,562)
  562 FORMAT('0>>>>> CHECK VALUE OF EPS')
      IF(VRATIO.LT.1..OR.VRATIO.GT.1.5)WRITE(NNPRNT,564)
  564 FORMAT('0>>>>> CHECK VALUE OF VRATIO')
      IF(US.LT.5.E-05.OR.US.GT.1.E-03)WRITE(NPENT,566)
  566 FORMAT('0>>>>> CHECK VALUE OF US')
      IF(FPATH.LT.0.5.OR.FPATH.GT.2.)WRITE(NNPRNT,568)
  568 FORMAT('0>>>>> CHECK VALUE OF FPATH')
      IF(EBD.LT.2.E+05.OR.EBD.GT.1.5E+06)WRITE(NNPRNT,570)
  570 FORMAT('0>>>>> CHECK VALUE OF EBD')
      IF(RHOCGS.LT.1.E+08.OR.RHOCGS.GT.1.E+14)WRITE(NNPRNT,572)
  572 FORMAT('0>>>>> CHECK VALUE OF RHO')
   73 IF(NRAPD.EQ.1)GO TO 79
      DO 78 I=2,NRAPD
      IF(ARD50(I).EQ.0.)WRITE(NNPRNT,574)
  574 FORMAT('0***** DATA MISMATCH:  NEED (NRAPD-1) VALUES OF ARD50')
      IF(ARSIGM(I).EQ.0.)WRITE(NNPRNT,576)
  576 FORMAT('0***** DATA MISMATCH:  NEED (NRAPD-1) VALUES OF ARSIGM')
   78 IF(ARSIGM(I).LT.1.)WRITE(NNPRNT,578)I
  578 FORMAT('0***** ARSIGM(',I2,') IS OUTSIDE ALLOWED RANGE')
   79 DO 84 I=1,NONID
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     IF(ASNUCK(I).LT.0..OR.ASNUCK(I).GT.1.)WRITE(NNPRNT,580)I
 580 FORMAT('0***** ASNUCK(',I2,') IS OUTSIDE ALLOWED RANGE')
     IF(AZIGGY(I).LT.0.)WRITE(NNPRNT,582)I
 582 FORMAT('0***** AZIGGY(',I2,') IS OUTSIDE ALLOWED RANGE')
     D=AZNUMS(I)-AINT(AZNUMS(I))
  84 IF(D.NE.0.)WRITE(NNPRNT,584)
 584 FORMAT('0***** AZNUMS MUST BE A WHOLE NUMBER')
     DO 86 J=1,NENDPT
  86 IF(ENDPT(J).EQ.0.)WRITE(NNPRNT,586)
 586 FORMAT('0***** MISSING DATA:  NEED NENDPT VALUES OF ENDPT')
     DO 88 J=1,NS
  88 IF(ENDPT(J+1).LE.ENDPT(J))WRITE(NNPRNT,588)
 588 FORMAT('0***** EACH ENDPT MUST BE > PRECEDING VALUE')
     IF(ENDPT(1).LT.0.01)WRITE(NNPRNT,590)
 590 FORMAT('0***** FIRST ENDPT MUST BE = OR > 0.01 UM')
  91 IF(NDIST.EQ.1)GO TO 96
     IF(D50.LT.0.1.OR.D50.GT.50.)WRITE(NNPRNT,592)
 592 FORMAT('0>>>>> CHECK VALUE OF D50')
     IF(SIGMAP.LT.1.)WRITE(NNPRNT,594)
 594 FORMAT('0***** SIGMAP IS OUTSIDE ALLOWED RANGE')
     GO TO 101
  96 IF(PRCU(1).NE.0.)WRITE(NNPRNT,596)
 596 FORMAT('0***** PRCU(1) MUST = 0.0 %')
     IF(PRCU(NENDPT).NE.100.)WRITE(NNPRNT,598)
 598 FORMAT('0***** LAST PRCU MUST = 100 %')
     DO 100 J=1,NS
 100 IF(PRCU(J+1).LE.PRCU(J))WRITE(NNPRNT,600)
 600 FORMAT('0***** EACH PRCU MUST BE > PRECEDING VALUE')
 101 IF(NDATA.GT.1)GO TO 200
     IF(NUMSEC.LT.1.OR.NUMSEC.GT.10)WRITE(NNPRNT,602)
 602 FORMAT('0***** NUMSEC IS OUTSIDE ALLOWED RANGE')
     LTOT = 0
     DO 105 I=1,NUMSEC
     IF(LSECT(I).LE.0)WRITE(NNPRNT,604)I
 604 FORMAT('0**** LSECT(',I2,') IS OUTSIDE ALLOWED RANGE')
 105 LTOT = LTOT+LSECT(I)
     IF(LTOT.GT.99)WRITE(NNPRNT,606)
 606 FORMAT('0***** SUM OF LSECT(I) > 99')
     PLINC = 0.
     DO 145 I=1,NUMSEC
     IF(MODL.EQ.1)GO TO 125
     IF(AS(I).LT.10..OR.AS(I).GT.1.E+06)WRITE(NNPRNT,608)I
 608 FORMAT('0>>>>> CHECK VALUE OF AS(',I2,')')
     IF(WLS(I).LT.1..OR.WLS(I).GT.1.E+06)WRITE(NNPRNT,610)I
 610 FORMAT('0>>>>> CHECK VALUE OF WLS(',I2,')')
     IF(ACS(I).LT.1.E-04.OR.ACS(I).GT.0.4)WRITE(NNPRNT,612)I
 612 FORMAT('0>>>>> CHECK VALUE OF ACS(',I2,')')
     IF(BS(I).LT.1..OR.BS(I).GT.20.)WRITE(NNPRNT,614)I
 614 FORMAT('0>>>>> CHECK VALUE OF BS(',I2,')')
     IF(SYS(I).LT.1..OR.SYS(I).GT.20.)WRITE(NNPRNT,616)I
 616 FORMAT('0>>>>> CHECK VALUE OF SYS(',I2,')')
     IF(VGS(I).LT.100..OR.VGS(I).GT.1.E+07)WRITE(NNPRNT,618)I
 618 FORMAT('0>>>>> CHECK VALUE OF VGS(',I2,')')
```

```
      IF(VGASS(I).LT.1..OR.VGASS(I).GT.10.)WRITE(NNPRNT,620)I
  620 FORMAT('0>>>>> CHECK VALUE OF VGASS(',I2,')')
      IF(TEMPS(I).LT.100..OR.TEMPS(I).GT.1000.)WRITE(NNPRNT,622)I
  622 FORMAT('0>>>>> CHECK VALUE OF TEMPS(',I2,')')
      IF(LINCS(I).LT.0.5.OR.LINCS(I).GT.2.)WRITE(NNPRNT,624)I
  624 FORMAT('0>>>>> CHECK VALUE OF LINCS(',I2,')')
      FV=5.*BS(I)*VGASS(I)*AS(I)/VGS(I)/LINCS(I)/FLOAT(LSECT(I))
      IF(FV.GT.1.05.OR.FV.LT.0.95)WRITE(NNPRNT,625)I,I
  625 FORMAT('0***** VGS(',I2,') AND VGASS(',I2,') DO NOT CORRELATE',
     1' WITH PLATE GEOMETRY')
      GO TO 126
  125 IF(AS(I).LT.1..OR.AS(I).GT.1.E+05)WRITE(NNPRNT,608)I
      IF(WLS(I).LT..3.OR.WLS(I).GT.1.E+05)WRITE(NNPRNT,610)I
      IF(ACS(I).LT.1.E-03.OR.ACS(I).GT.10.)WRITE(NNPRNT,612)I
      IF(BS(I).LT..03.OR.BS(I).GT..5)WRITE(NNPRNT,614)I
      IF(SYS(I).LT..03.OR.SYS(I).GT..5)WRITE(NNPRNT,616)I
      IF(VGS(I).LT..05.OR.VGS(I).GT.5.E+03)WRITE(NNPRNT,618)I
      IF(VGASS(I).LT..3.OR.VGASS(I).GT.3.)WRITE(NNPRNT,620)I
      IF(TEMPS(I).LT.50..OR.TEMPS(I).GT.500.)WRITE(NNPRNT,622)I
      IF(LINCS(I).LT.0.1.OR.LINCS(I).GT..7)WRITE(NNPRNT,624)I
      FV=BS(I)*VGASS(I)*AS(I)/VGS(I)/LINCS(I)/FLOAT(LSECT(I))
      IF(FV.GT.1.05.OR.FV.LT.0.95)WRITE(NNPRNT,625)I,I
  126 IF(VOS(I).LT.1.E+03.OR.VOS(I).GT.1.E+05)WRITE(NNPRNT,626)I
  626 FORMAT('0>>>>> CHECK VALUE OF VOS(',I2,')')
      IF(TCS(I).LT.1.E-04.OR.TCS(I).GT.10.)WRITE(NNPRNT,628)I
  628 FORMAT('0>>>>> CHECK VALUE OF TCS(',I2,')')
      IF(NWS(I).LT.1.)WRITE(NNPRNT,630)I
  630 FORMAT('0***** NWS(',I2,') IS OUTSIDE ALLOWED RANGE')
      IF(PS(I).LT.0.5.OR.PS(I).GT.1.5)WRITE(NNPRNT,632)I
  632 FORMAT('0>>>>> CHECK VALUE OF PS(',I2,')')
      IF(VISS(I).LT.1.7E-5.OR.VISS(I).GT.3.E-5)WRITE(NNPRNT,634)I
  634 FORMAT('0>>>>> CHECK VALUE OF VISS(',I2,')')
      PLINC = PLINC + LSECT(I)*LINCS(I)
      IF(NVI.EQ.1)GO TO 145
      IF(RFS(I).LT.0.5.OR.RFS(I).GT.1.)WRITE(NNPRNT,636)I
  636 FORMAT('0>>>>> CHECK VALUE OF RFS(',I2,')')
      IF(START1(I).EQ.0.)WRITE(NNPRNT,638)I
  638 FORMAT('0***** MISSING VARIABLE:  START1(',I2,')')
      IF(START2(I).EQ.0.)WRITE(NNPRNT,640)I
  640 FORMAT('0***** MISSING VARIABLE:  START2(',I2,')')
      IF(START3(I).EQ.0.)WRITE(NNPRNT,642)I
  642 FORMAT('0***** MISSING VARIABLE:  START3(',I2,')')
      IF(VSTAR(I).LT.1.E+03)WRITE(NNPRNT,644)
  644 FORMAT('0>>>>> FOR FASTER CONVERGENCE SET VSTAR CLOSE TO VOS')
  145 CONTINUE
      IF(MODL.EQ.1)GO TO 146
      IF(PLINC.LT.PLB-1..OR.PLINC.GT.PLB+1.)WRITE(NNPRNT,646)
  646 FORMAT('0***** LSECT * LINCS MUST = SECTION LENGTH')
      GO TO 200
  146 IF(PLINC.LT.PL-0.5.OR.PLINC.GT.PL+0.5)WRITE(NNPRNT,646)
      GO TO 200
  147 DO 150 I=1,NUMSEC
      IF(MODL.EQ.1)GO TO 148
      IF(VGS(I).LT.100..OR.VGS(I).GT.1.E+07)WRITE(NNPRNT,618)I
      IF(VGASS(I).LT.1..OR.VGASS(I).GT.10.)WRITE(NNPRNT,620)I
      GO TO 150
  148 IF(VGS(I).LT..05.OR.VGS(I).GT.5.E+03)WRITE(NNPRNT,618)I
      IF(VGASS(I).LT..3.OR.VGASS(I).GT.3.)WRITE(NNPRNT,620)I
  150 CONTINUE
      GO TO 200
  151 DO 154 I=1,NUMSEC
      IF(VOS(I).LT.1.E+03.OR.VOS(I).GT.1.E+05)WRITE(NNPRNT,626)I
  154 IF(TCS(I).LT.1.E-04.OR.TCS(I).GT.10.)WRITE(NNPRNT,628)I
  200 RETURN
      END
      SUBROUTINE INTERN (NINT)                                          INT
C         $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C         $                                                                 $
C         $    EPRI/SRI 1982 CORRELATION OF COLD-SIDE ESP OPERATING POINTS  $
C         $                                                                 $
C         $    EPRI CONTRACT RP629-5     DR. R. F. ALTMAN, PROJECT MANAGER  $
C         $                                                                 $
C         $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      REAL LINCS,NWS
      INTEGER VISKIP,VISAME
      DIMENSION AJ(6),BJ(6),AE(6),BE(6),CUR(10),CURR(10),VOLT(6,10)
      DIMENSION AAMP(6),AAMPP(6)
      DIMENSION IBLNK(21),ISCA(4)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DO,ETAO,DL,PL,RHO
      COMMON/BLK4/WS
      COMMON/BLK5/ZMMD1,SIGMI,MDMID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,OFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),SW(77),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SVS(10),VCS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,DC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMAS
      COMMON/BLK11/ENDPT(21),NENDPT
      COMMON/BLK12/ARD50(10),ARSIGM(10),ASHUCK(15),AZNUMS(15),AZIGGY(15)
      COMMON/BLK14/TMFF,NVI
      COMMON/BLK16/NCALC,NI,VRATIO,NF
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK19/LX,IW,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1J11,J12,VISKIP,VISAME,US,FPATH,E30,NDSET,NWS(10),D50,SIGMAP,
     2PAIRL,NCOMPS,NWAVES,NLAMDA,NRAP,MODL,NOPRNT
      DATA ISCA/' 2',' 4',' 6',' 8'/
      DATA CUR/1.,2.,4.,6.,9.,12.,16.,20.,30.,40./
      DATA AJ/ 6.455, 6.839, 5.497, 5.718, 3.328, 3.328/
      DATA BJ/-0.5013,-0.5214,-0.3905,-0.4005,-0.1736,-0.1736/
      DATA AE/-3.5294,-3.4209,-3.1735,-2.3430,-3.1818,-3.1818/
      DATA BE/ 8.3841, 8.6546, 8.5755, 7.5195,10.0909,10.0909/
      RHO=RHO*100.
      NINT=NINT+1
      IF(NINT.GE.5)RETURN
      IF(NINT.GT.1)GO TO 30
      READ(NREAD,1000)RHO,NDUCT
 1000 FORMAT(E8.2,2X,F5.2)
      RHOLOG=ALOG10(RHO)
      NAFDUC=NDUCT*2.54
      DO 21 K=1,6
C
C  CALCULATE THE VI CURVE IN SECTION K
      DO 14 M=1,10
      AMP=ALOG10(CUR(M))
      EFIELD=(AMP-AE(K))/BE(K)
      EFIELD=10.0**EFIELD
      VOLT(K,N)=EFIELD*HAFDUC
   14 CURR(N)=CUR(N)/1.0764
C
C  CALCULATE THE OPERATING POINT IN SECTION K
      AAMP(K)=AJ(K)+BJ(K)*RHOLOG
      IF(K.EQ.1.AND.AAMP(K).GT.1.4299)AAMP(K)=1.4299
      IF(AAMP(K).GT.1.7309)AAMP(K)=1.7309
      IF(AAMP(K)+RHOLOG.GT.13.1761)AAMP(K)=13.1761-RHOLOG
      FIELD=(AAMP(K)-AE(K))/BE(K)
      FIELD=10.0**FIELD
      VOS(K)=FIELD*HAFDUC
      AAMP(K)=10.0**AAMP(K)
      AAMPP(K)=AAMP(K)/1.0764
   21 CONTINUE
C
C  WRITE VI CURVE
      WRITE(NPRNT,5800)
 5800 FORMAT(1H1)
      WRITE(NPRNT,5850)
 5850 FORMAT(40X,'**************************************')
      WRITE(NPRNT,5851)
 5851 FORMAT(40X,'*',35X,'*')
      WRITE(NPRNT,5852)
 5852 FORMAT(40X,'*',9X,'E.P.A. ESP MODEL',10X,'*')
      WRITE(NPRNT,5851)
      WRITE(NPRNT,5853)
 5853 FORMAT(40X,'*',4X,'I.E.R.L.-R.T.P. AND SO.R.I.',4X,'*')
      WRITE(NPRNT,5851)
      WRITE(NPRNT,5854)
 5854 FORMAT(40X,'*',12X,'REVISION III',11X,'*')
      WRITE(NPRNT,5851)
      WRITE(NPRNT,5850)
      WRITE(NPRNT,125)RHO,HAFDUC
  125 FORMAT(///' EPRI/SRI 1982 CORRELATION OF COLD SIDE ESP OPERATING '
     1,'POINTS'//' EPRI CONTRACT RP629-5     DR. R. F. ALTMAN, PROJECT '
     2,'MANAGER'///' INPUT DATA:   RESISTIVITY            =',1PE11.2
     3,' OHM-CM'//'                WIRE-TO-PLATE SPACING =',0PF7.2,' CM')
      DO 23 K=1,6
      WRITE(NPRNT,115)K
  115 FORMAT(///' V-I CURVE DATA FOR SECTION',I2)
      WRITE(NPRNT,116)(VOLT(K,N),N=1,10)
  116 FORMAT(//'    KILOVOLTS:  ',10F6.2)
      WRITE(NPRNT,117)(CUR(N),N=1,10)
  117 FORMAT(//'    NA/CM2:     ',10F6.2)
      WRITE(NPRNT,118)(CURR(N),N=1,10)
  118 FORMAT(//'    UA/FT2:     ',10F6.2)
      WRITE(NPRNT,119)K
  119 FORMAT(//' THE OPERATING POINT FOR SECTION',I2,' IS:')
      WRITE(NPRNT,120)VOS(K),AAMP(K),AAMPP(K)
  120 FORMAT(//'    KILOVOLTS: ',F8.2/'    NA/CM2:    ',F8.2,/'    UA/FT2:
     1    ',F8.2)
   23 CONTINUE
```

```
      IF(MODL.EQ.2)GO TO 28
      NINT=6
      RETURN
   28 DO 29 K=1,6
      VOS(K)=VOS(K)*1000.
      BS(K)=HDUCT
   29 CONTINUE
   30 NENDPT=17
      NDATA=1
      NDIST=2
      NVI=1
      NX=10
      NY=10
      NITER=2
      NCALC=1
      NRAPD=1
      NEFF=1
      NTEMP=1
      NONID=2
      NN=5
      NS=16
      DL=4.01
      ETAO=98.5
      DD=2270.
      EPS=100.
      VRATIO=1.2
      US=.00022
      FPATH=1.
      EBD=1500000.
      NEST=2
      NOPRNT=2
      PATHL=0.0
      ASNUCX(1)=0.0
      AZIDBY(1)=0.0
      ASNUCX(2)=0.10
      AZIDBY(2)=0.25
      ENDPT(1)=0.075
      ENDPT(2)=0.125
      ENDPT(3)=0.175
      ENDPT(4)=0.225
      ENDPT(5)=0.275
      ENDPT(6)=0.625
      ENDPT(7)=0.975
      ENDPT(8)=1.425
      ENDPT(9)=1.975
      ENDPT(10)=3.025
      ENDPT(11)=3.975
      ENDPT(12)=5.025
      ENDPT(13)=6.975
      ENDPT(14)=13.025
      ENDPT(15)=14.975
      ENDPT(16)=25.025
      ENDPT(17)=29.975
      D50=15.0
      SIGMAP=3.0
      DO 40 K=1,6
      LSECT(K)=10
      TEMPS(K)=300.
      ACS(K)=5.3E-02
      WLS(K)=5.2E+04
      NWS(K)=12.
      PS(K)=1.
      VISS(K)=2.2E-05
   40 CONTINUE
C
C  CALCULATE ESP GEOMETRY
      NUMSEC=2*NINT
      IF(NINT.EQ.4)NUMSEC=6
      AZNUMS(1)=NUMSEC
      AZNUMS(2)=NUMSEC
      PL=18*FLOAT(NINT)
      DO 50 K=1,6
      AS(K)=2.0E+04
      VGS(K)=3.0E+05
      IF(NINT.EQ.4)VGS(K)=1.5E+05
      LINCS(K)=0.9
      IF(NINT.EQ.4)LINCS(K)=1.2
      TCS(K)=AMPP(K)*0.02
      SYS(K)=5*LINCS(K)
      VGASS(K)=10./HDUCT
   50 CONTINUE
      RHO=RHO/100.
      PL=PL*.05
      DL=DL*2.9E-03
      DV=DL/D0
      IF(NINT.EQ.1)ITL(4)=ISCA(1)
      IF(NINT.EQ.2)ITL(4)=ISCA(2)
      IF(NINT.EQ.3)ITL(4)=ISCA(3)
      IF(NINT.EQ.4)ITL(4)=ISCA(4)
      RETURN
      END
      BLOCK DATA
      COMMON/GAUSS/T(3),WGAUS(3)
      COMMON/OPACTY/CMR(10),CMI(10),UPTOLM(10),NTIMES,NCOMP,NNCOMP        OPAC
     1,DELTAD(20),DMDLD(20),RDMDLD(20),CDMDLD(20),TOTOPA(2),TOTNRP(2)    OPAC
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(99),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10),CMKS
      DATA T/-0.77459667,0.0,0.77459667/
      DATA WGAUS/0.55555556,0.88888889,0.55555556/
      DATA CMR(1)/1.5/,CMR(2)/1.5/,CMI(1)/-0.0/,CMI(2)/-0.10/,NTIMES/1/  OPAC
      DATA ITL(1)/' S'/,ITL(2)/'CA'/,ITL(3)/' ='/,ITL(5)/'00'/
      END
```